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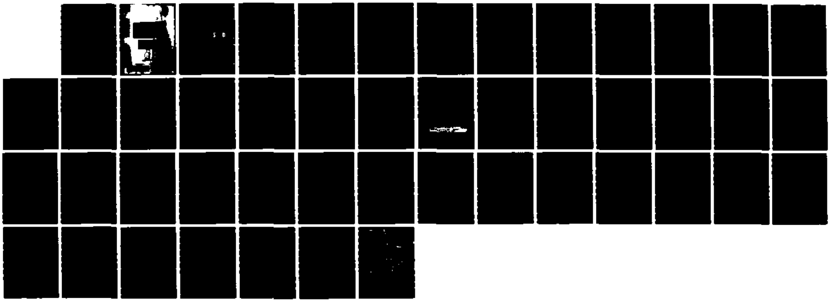

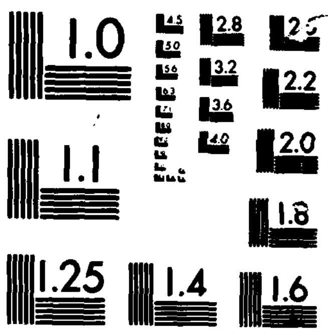

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ROBERT TAGGART INCORPORATED

AD-A167 744

FORCES AND MOMENTS

ON SHIPS TO BE MOORED

AT DIEGO GARCIA

ENGINEERING RESEARCH

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AD-A167 744

FORCES AND MOMENTS ON SHIPS TO BE MOORED AT DIEGO GARCIA

SUBMITTED TO

OCEAN ENGINEERING AND CONSTRUCTION PROJECT OFFICE
CHESAPEAKE DIVISION
NAVAL FACILITIES ENGINEERING COMMAND

JULY 1980

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The technique use to calculate wind forces and moments on a given ship is delineated in Chapter XII, Section 1 of the forthcoming book "Ship Design and Construction". The pertinent material is reproduced in Appendix A of this report. Basically the abovewater area is divided into layers of (Con't)

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equivalent area. A wind velocity profile is assumed wherein the velocity varies as the one-fifth power of the height above the surface of the water and the drag forces for a bow-on and for a beam-on wind are calculated. Multipliers, derived from past experience and model tests, are applied to these forces to derive the resultant forces and moments for winds acting at various angles from bow-on to stern-on. Current forces are also derived.

WIND AND CURRENT FORCE AND MOMENT CALCULATIONS

The technique used to calculate wind forces and moments on a given ship is delineated in Chapter XII, Section 1 of the forthcoming book "Ship Design and Construction". The pertinent material is reproduced in Appendix A of this report. Basically the abovewater area is divided into layers of equivalent area. A wind velocity profile is assumed wherein the velocity varies as the one-fifth power of the height above the surface of the water and the drag forces for a bow-on and for a beam-on wind are calculated. Multipliers, derived from past experience and model tests, are applied to these forces to derive the resultant forces and moments for winds acting at various angles from bow-on to stern-on. Current forces are also derived.

MERCHANT SHIP CALCULATIONS

The ships on which these calculations were made are the Maine Class Ro/Ro merchant ships (MarAd Designation C7-S-95a), Figure 1, and the Challenger II Class General Cargo Ships (MarAd Designation C4-S-64a). The general characteristics of these vessels are given in Table 1 below:

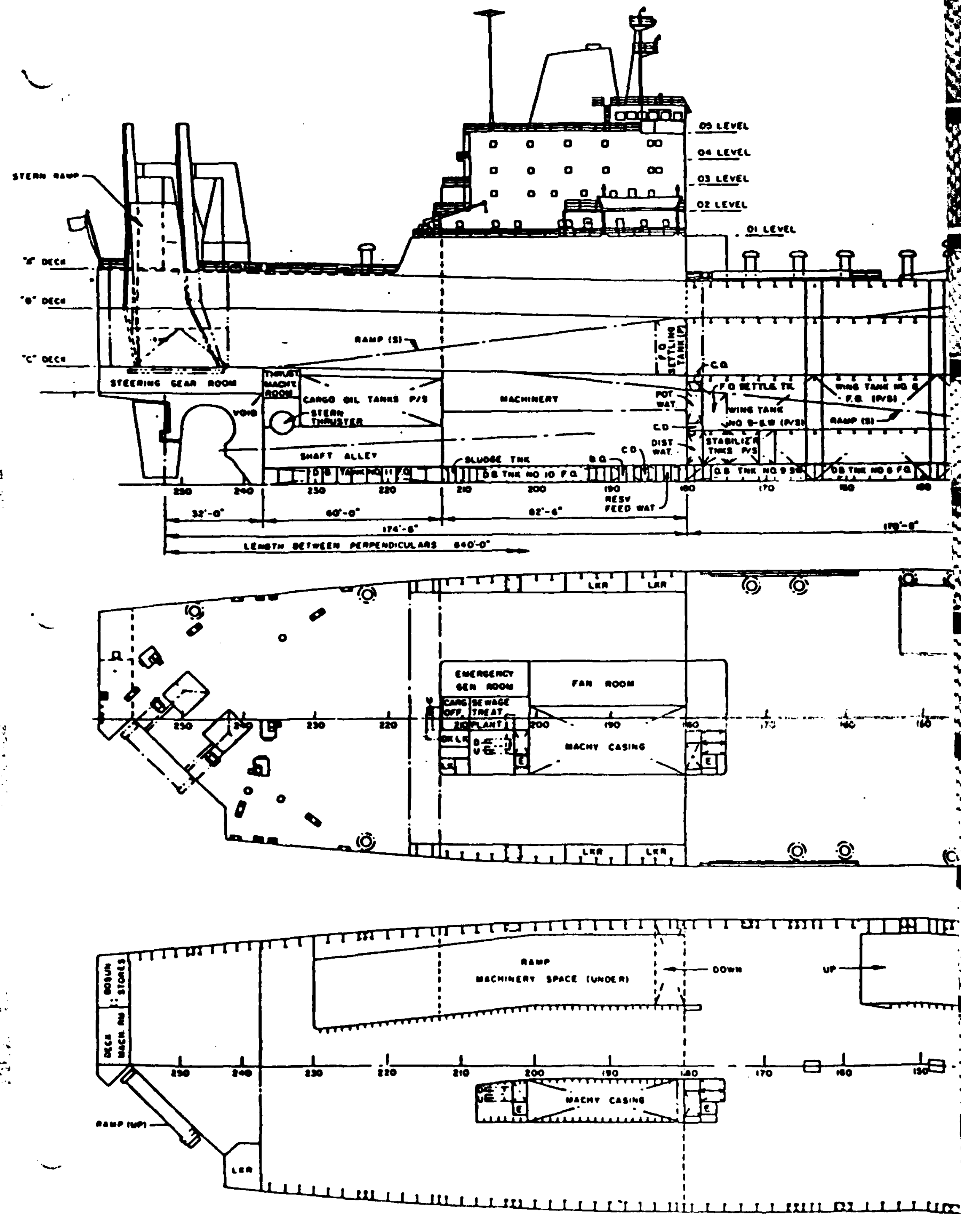
Table 1: Dimensions of Merchant Ships

Characteristic	C7-S-94a	C4-S-64a
Length overall, feet	684.0	544.0
Beam, max, feet	102.0	75.0
Depth to main deck, feet	69.5	42.5
Assigned draft, feet	32.0	31.7
Load displacement, tons	33640	19800

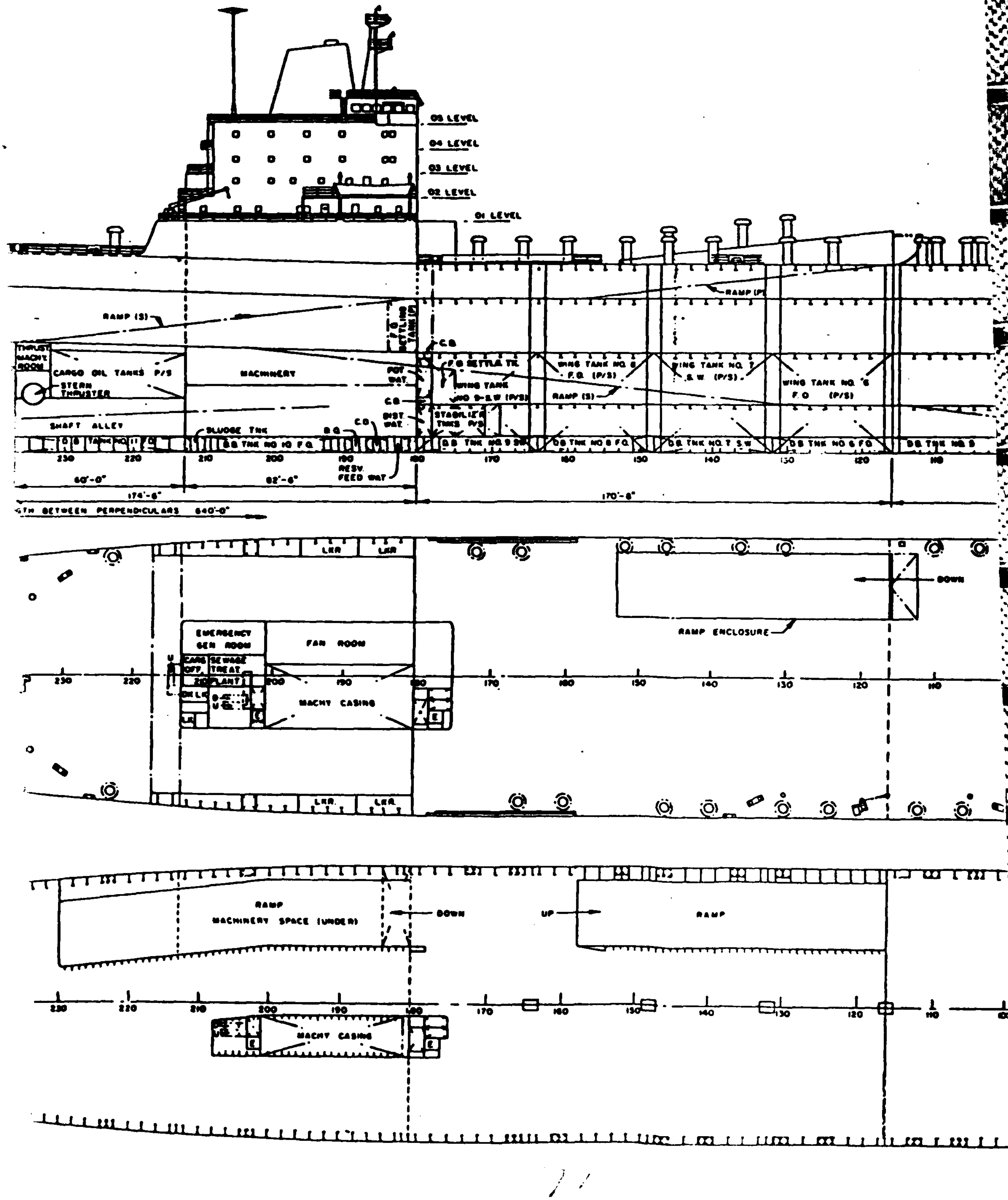
The latter is similar in abovewater characteristics to Figure 2.

Of the various types of merchant ships to be moored at Diego Garcia, the C7-S-95a will apply the maximum wind and current forces of those vessels to be secured by a single point moor. The C4-S-64a cargo ship will apply the maximum forces of any merchant ship to be secured by a two point moor. Thus calculations of the forces acting on these two ships will cover adequately the vessels in the merchant ship category.

The basic dimensions for wind force calculations of the C7-S-95a are given in Table 2. In this table the following symbols are utilized:



03 LEVEL
04 LEVEL
03 LEVEL
02 LEVEL
01 LEVEL
STERN RAMP
"A" DECK
"B" DECK
"C" DECK
RAMP (S)
STEERING GEAR ROOM
THRUST MACH'Y ROOM
CARGO OIL TANKS P/S
MACHINERY
VOID
STERN THRUSTER
SHAFT ALLEY
SLUDGE TNK
F.O. SETTLING TANK (P)
F.O. SETTLE TK
POT WAT
C.D.
DIST WAT
WING TANK NO 9-S.W (P/S)
WING TANK NO 8 F.O. (P/S)
RAMP (S)
STABILIZR TNKS P/S
DB TNK NO 10 F.O.
DB TNK NO 9
DB TNK NO 8 F.O.
RESV FEED WAT
32'-0"
60'-0"
82'-6"
174'-6"
170'-6"
LENGTH BETWEEN PERPENDICULARS 640'-0"
LKR
EMERGENCY GEN ROOM
FAN ROOM
CARG OFF
SEWAGE TREAT PLANT
MACHY CASING
RAMP
MACHINERY SPACE (UNDER)
DOWN
UP
BOSUN STORES
DECK MACH. RM
RAMP (UP)



05 LEVEL
04 LEVEL
03 LEVEL
02 LEVEL
01 LEVEL
RAMP (S)
RAMP (P)
THRUST MACHY ROOM
CARGO OIL TANKS P/S
STERN THRUSTER
MACHINERY
SHAFT ALLEY
SLUDGE TNK
F.O. SETTLING TANK (P)
C.O.
F.O. SETTL'G TK
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WING TANK NO. 9 - S.W. (P/S)
WING TANK NO. 8 F.O. (P/S)
WING TANK NO. 7 S.W. (P/S)
WING TANK NO. 6 F.O. (P/S)
RAMP (S)
DIST. WAT.
STABILIZ'R TNKS P/S
D.B. TNK NO 10 F.O.
D.B. TNK NO 9 S.W.
D.B. TNK NO 8 F.O.
D.B. TNK NO 7 S.W.
D.B. TNK NO 6 F.O.
D.B. TNK NO 5
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GTH BETWEEN PERPENDICULARS 640'-0"
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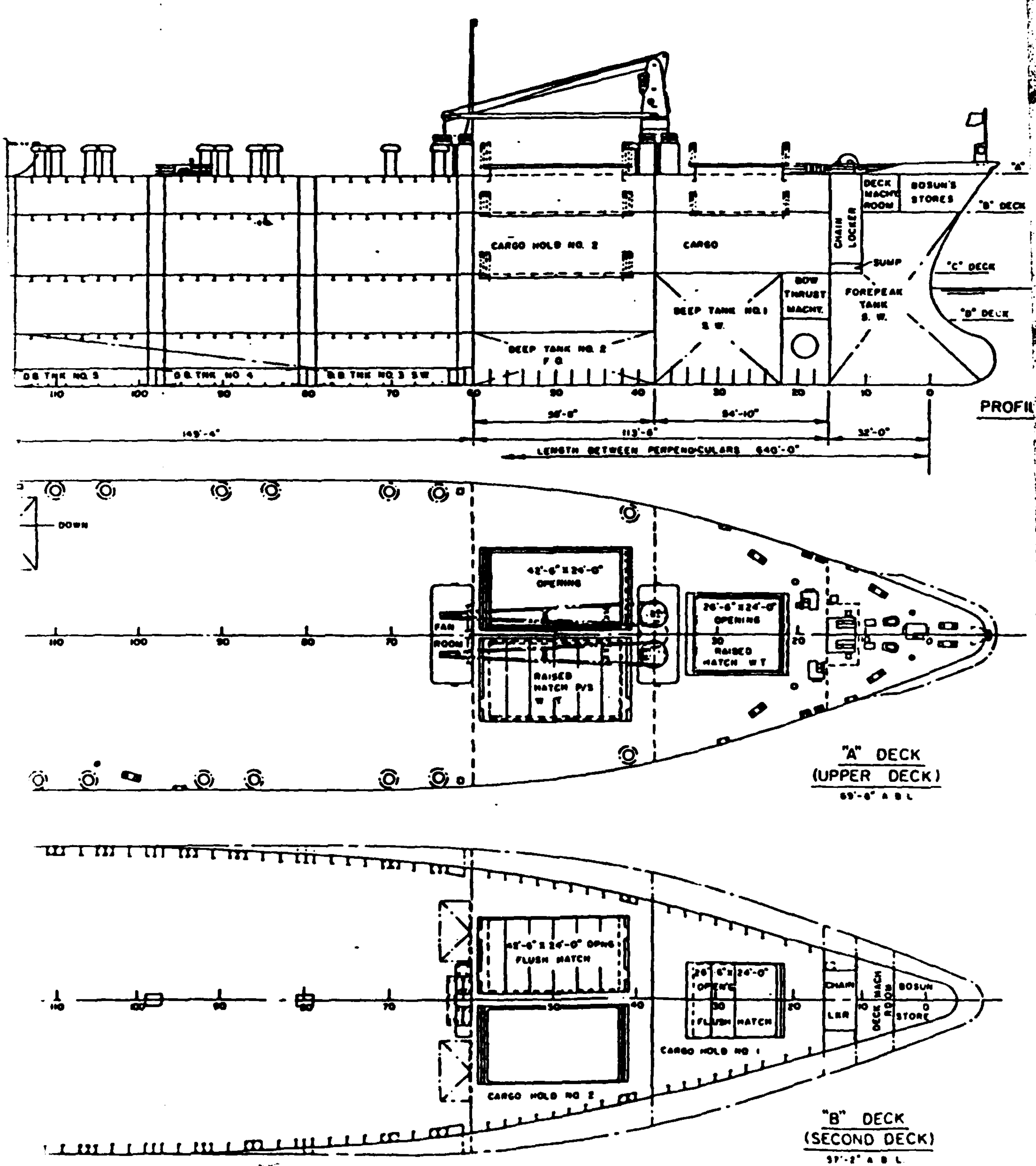
EMERGENCY GEN ROOM
FAN ROOM
CARG OFF.
SEWAGE TREAT PLANT
MACHY CASING
RAMP ENCLOSURE
DOWN
RAMP
MACHINERY SPACE (UNDER)
UP
230
220
210
200
190
180
170
160
150
140
130
120
110

MAINE CLASS Ro/Ro SHIP

C7-S-94a

FIGURE 1



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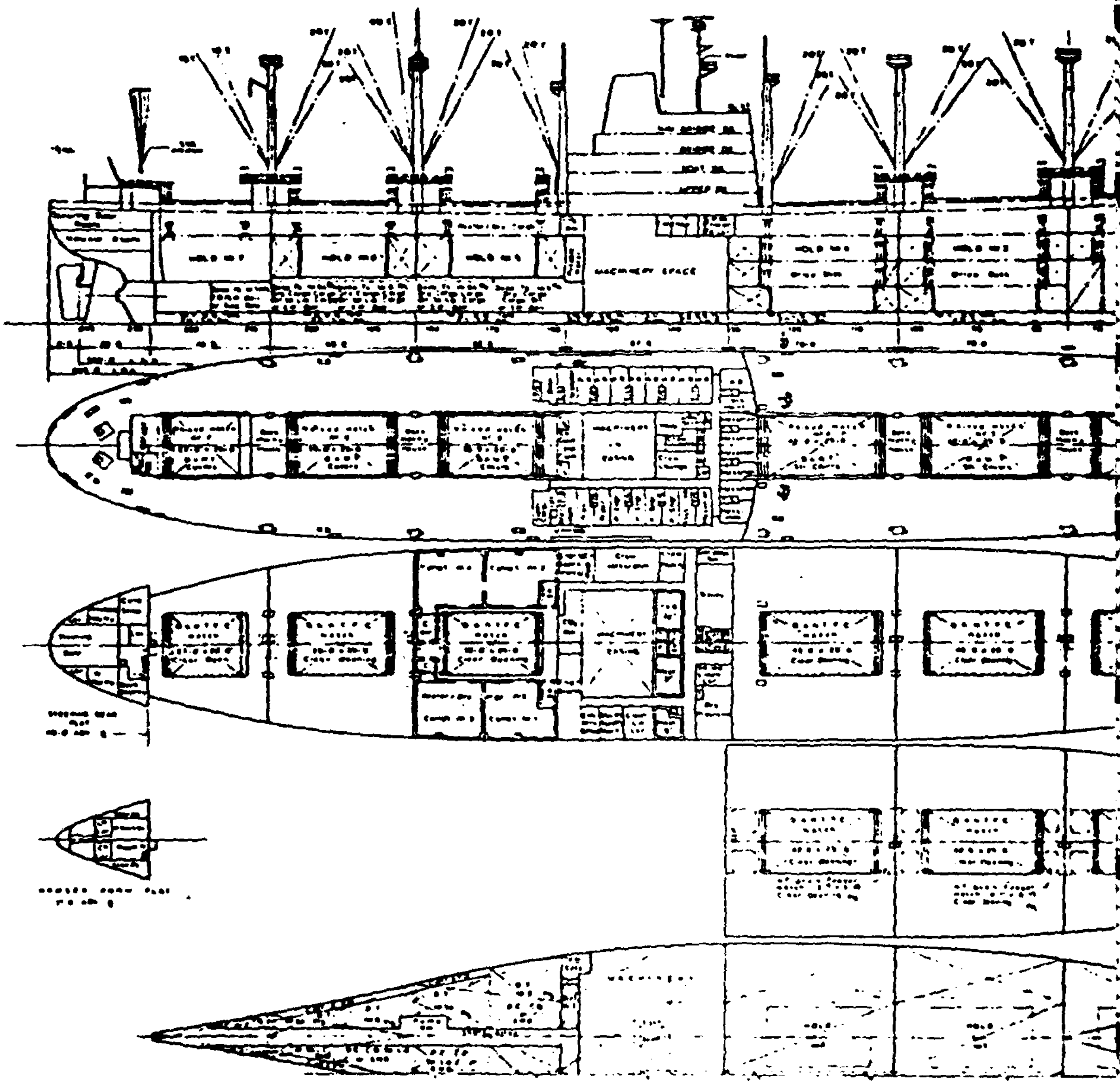
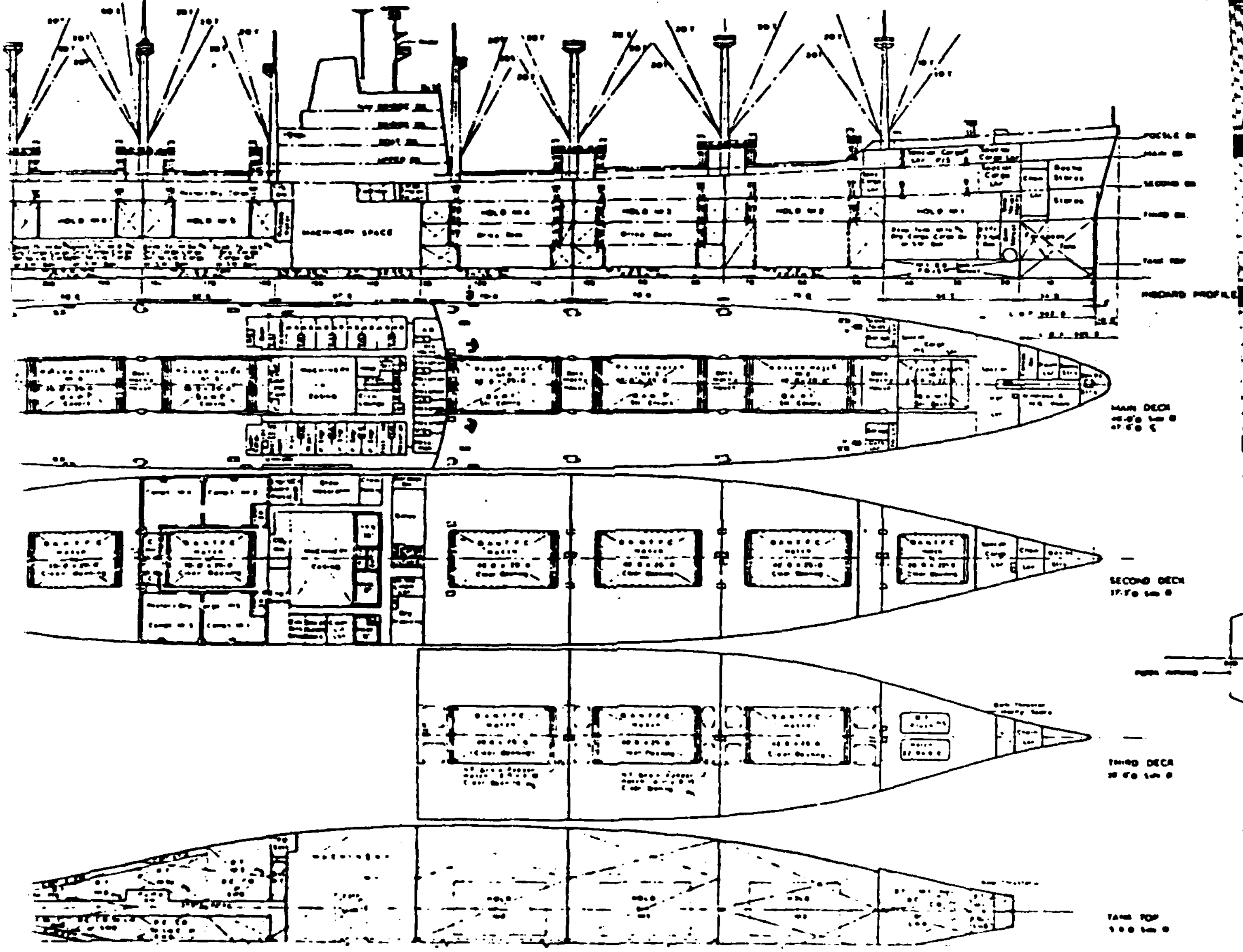
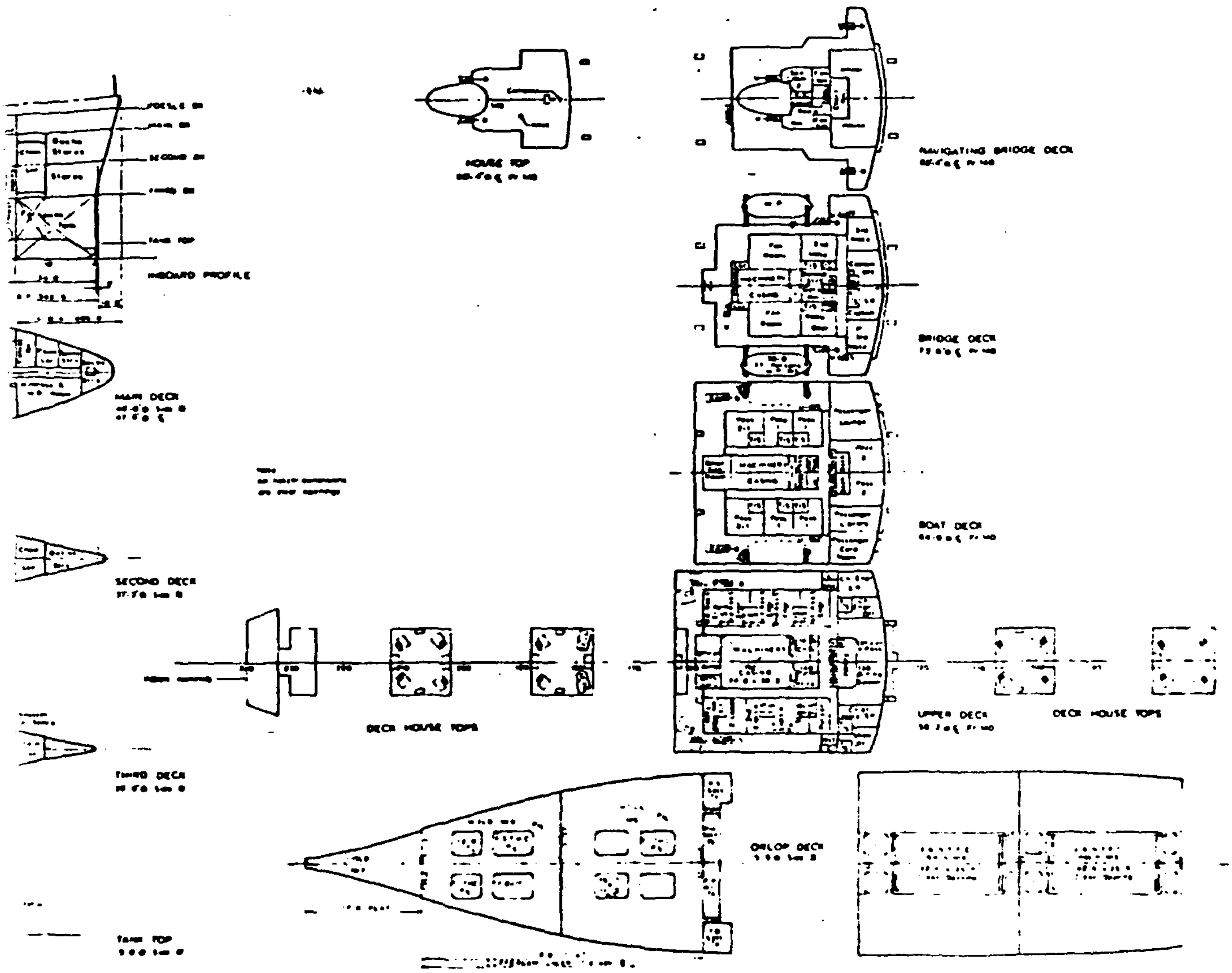

MACHINERY SPACE


INBOARD PROFILE
MAIN DECK
SECOND DECK
THIRD DECK
TANK TOP

BREAK-BULK CARGO SHIP

C5-S-75a

FIGURE 2



h = height above waterline
ℓ = effective length at designated height
b = effective beam at designated height
M = multiplier for force from layer
F_T = lateral 40 knot wind force on layer in kips
F_L = longitudinal 40 knot wind force on layer in kips
LCR = center of pressure of wind force from ⊗ in feet

Table 2: C7-S-95a Wind Force Calculations

h	ℓ	b	M	F_T	F_L	LCR
0	663	102				
			185	124.6	27.7	-8
38.15	683	197				
			79	40.4	15.6	-57
49.22	334	197				
			68	17.0	10.2	-105
58.01	162	102				
			56	8.1	5.3	-185
64.87	124	85				
			93	11.4	7.9	-192
75.59	121	85				
			64	6.6	5.4	-188
82.63	86	85				
			83	7.0	7.8	-181
91.42	83	102				
			86	5.7	6.5	-178
100.21	50	49				
			154	6.3	5.4	-176
115.15	32	21				
			129	2.6	1.9	-162
127	9	9				
	Totals		F_{T_0} =	229.8		
			F_{L_0} =		93.8	
			LCR =			-60.2

Profiles and sections of the Challenger II Class were not available. However, this ship is almost identical in appearance to the C5-S-75a shown in Figure 2. Comparable dimensions of the two ships are given in Table 3.

Table 3: Dimensions in Feet of Comparable Break-Bulk Cargo Ships

	Challenger II	C5-S-75a	Ratio
Length Overall	544.0	605.0	0.899
Length on Waterline	521.2	582.7	0.894
Beam, Maximum	75.0	82.0	0.915
Depth to Main Deck	42.5	46.0	0.924
Assigned Draft	31.7	35.0	0.906
Freeboard	10.8	11.0	0.982

The wind force calculations for the C5-S-75a are given in Appendix A where this was used as the sample ship to illustrate the calculation technique. Thus the ratios above can be applied to length and beam measurements; the heights are unchanged since the freeboard, king post, and deck heights for the two ships are nearly identical. The results must also be converted from the SI units used with the following results:

$$F_{T_0} = 127{,}515\#$$

$$F_{L_0} = 54{,}486\#$$

$$LCR = 0.897 \times 0.64 \div 0.3048 = 1.88 \text{ ft fwd}$$

for a 40 knot wind speed.

Using the flow force and center multipliers tabulated in Appendix A, the longitudinal and transverse forces as functions of wind angle can then be calculated together with the resultant wind force, the center of lateral resistance, and the wind moment. These are listed for the Maine Class Ro/Ro in Table 4 and for the Challenger II Class in Table 5.

Table 4: Wind Forces and Moments for the Maine Class Ro/Ro as Functions of Wind Direction

Wind Angle $\alpha°$	F_L Kips	F_T Kips	F_R Kips	*LCR*, Ft Fwd ⊗	Moment Ft-Kips
0	93.8	0	93.8	----	------
10	102.0	40.0	109.5	141	5638
20	103.9	78.6	146.7	141	11082
30	140.7	114.9	181.7	141	16201
40	131.3	147.8	197.7	121	17880
50	105.5	176.0	205.2	107	18836
60	70.3	199.0	211.1	71	14130
70	35.1	216.0	218.9	30	6481
80	9.4	226.4	226.6	-7	-1585
90	0	229.8	229.8	-60	-13788
100	-9.4	226.4	226.6	-113	-25579
110	-35.1	216.0	218.9	-150	-32403
120	-70.3	199.0	211.1	-191	-38012
130	-105.5	176.0	205.2	-227	-39959
140	-131.3	147.8	197.7	-241	-35612
150	-140.7	114.9	181.7	-261	-29990
160	-123.9	78.6	146.7	-261	-20513
170	-102.0	40.0	109.5	-261	-10437
180	-93.8	0	93.8	----	------

Also acting on the two merchant ships are the forces applied by currents acting within the mooring area. For the purposes of these calculations the current has been assumed to be a maximum of one-half knot. If greater currents are anticipated, the forces will be in the ratio of the square of the ratio of the current speed to one-half knot.

As discussed in Appendix A, a fore and aft drag coefficient of 0.088 can be assumed. To this must be added the drag of locked propellers. For transverse resistance the relationship of depth of harbor to ship draft determines the drag coefficient. For the Maine Class this is estimated at $C_D = 1.20$ and for the Challenger II Class it is estimated at $C_D = 1.18$. The bow-on and the transverse one-half knot current forces for these two ships are therefore estimated at:

Table 5: Wind Forces and Moments for the Challenger II Class as Functions of Wind Direction

Wind Angle $\alpha°$	F_L Kips	F_T Kips	F_R Kips	LCR, Ft Fwd	Moment Ft-Kips
0	54.5	0	54.5	----	----
10	59.2	22.2	63.2	129.4	2873
20	72.0	43.6	84.2	129.4	5642
30	81.7	63.8	103.7	129.4	8256
40	76.3	82.0	112.0	116.7	9569
50	61.3	97.7	115.3	107.4	10493
60	40.9	110.4	117.7	84.1	9285
70	20.4	119.9	121.6	58.2	6978
80	5.4	125.6	125.7	34.4	4321
90	0	127.5	127.5	-1.9	-242
100	-5.4	125.6	125.7	-34.9	-4383
110	-20.4	119.9	121.6	-59.1	-7086
120	-40.9	110.4	117.7	-85.3	-9417
130	-61.3	97.7	115.3	-108.9	-10640
140	-76.3	82.0	112.0	-118.4	-9709
150	-81.7	63.8	103.7	-131.3	-8377
160	-72.0	43.6	84.2	-131.3	-5725
170	-59.2	72.2	63.2	-131.3	-2915
180	-54.5	0	54.5	----	----

Maine Class Ro/Ro:

F_{L_0} = 198# hull + 187# propeller = 386#

F_{T_0} = 18612#

Challanger II Class:

F_{L_0} = 144# hull + 171# propeller = 315#

F_{T_0} = 13815#

For both ships the LCR is at the midship section. The resulting force and moment versus current angle calculations are tabulated in Table 6 for the Maine Class Ro/Ro and in Table 7 for the Challenger II Class. Since the values are symmetrical only the first 90° of current angle off the bow are given.

Table 6: Current Forces and Moments versus Current Angle off the Bow for the Maine Class Ro/Ro

Current Angle $\alpha°$	F_L Kips	F_T Kips	F_R Kips	*LCR*, Ft Fwd ⊗	Moment Ft-Kips
0	0.4	0	0	---	----
10	0.4	1.3	1.4	171	230
20	0.4	3.7	3.7	171	637
30	0.3	6.6	6.6	171	1125
40	0.3	9.6	9.6	154	1479
50	0.2	12.5	12.5	142	1771
60	0.2	15.0	15.0	111	1667
70	0.1	17.0	17.0	77	1305
80	0.1	18.2	18.2	45	827
90	0	18.6	18.6	0	0

Table 7: Current forces and Moments versus Current Angle off the Bow for the Challenger II Class

Current Angle $\alpha°$	F_L Kips	F_T Kips	F_R Kips	*LCR*, Ft Fwd ⊗	Moment Ft-Kips
0	0.3	0	0.3	---	---
10	0.3	2.4	2.4	130	312
20	0.4	4.7	4.7	130	614
30	0.5	6.9	6.9	130	898
40	0.4	8.9	8.9	117	1039
50	0.4	10.6	10.6	108	1143
60	0.2	12.0	12.0	85	1017
70	0.1	13.0	13.0	59	766
80	0	13.6	13.6	35	476
90	0	13.8	13.8	0	0

MILITARY SHIP CALCULATIONS

Of the military ships to be moored at Diego Garcia there are two nests of ships that are of primary concern. These are a submarine tender with a number of submarines alongside for repair and a destroyer tender with a number of destroyers alongside for repair. The latter nest of ships obviously represents the worst case so that will be treated in the following calculations.

It is assumed that the destroyer tender will be the *SAMUEL GOMPERS*, AD 37 Class, and that the destroyers will be the *SPRUANCE*, DD 963 Class. The overall dimensions of these vessels are given in Table 8.

Table 8: Overall Characteristics of Military Ships (Figures 3 and 4)

	AD 37	DD 963
Length Overall, ft	643.0	563.2
Length on Waterline, ft	613.0	529.0
Beam, ft	85.0	55.0
Draft, loaded, ft	26.0	19.0
Displacement, loaded, tons	21,000	7810

Wind force calculations have been made for each of these two ships as described previously. The calculations for the basic longitudinal and transverse wind forces and the center of lateral resistance for the *SAMUEL GOMPERS* are tabulated in Table 9 and for the *SPRUANCE* in Table 10.

Table 9: *SAMUEL GOMPERS* Wind Force Calculations

h	ℓ	b	M	F_T	F_L	LCR
0	616	85				
			280	176.3	23.8	0
51.24	643	85				
			69	41.7	5.9	0
60.03	557	85				
			49	24.6	4.2	+2
65.93	448	85				
			41	18.4	4.0	+1
70.75	444	110				
			121	39.2	13.3	+34
84.15	204	110				
			185	22.4	13.4	+8
103.13	39	35				
			199	6.2	5.9	-3
122.10	24	24				
			316	9.8	9.6	+37
150.08	38	37				
			341	7.7	7.5	+73
178.06	7	7				
			Totals	346.3	87.6	+10.6

Table 10: *SPRUANCE* Wind Force Calculations

h	ℓ	b	M	F_T	F_L	LCR
0	530	55				
			45	24.1	2.5	+2
13.94	543	55				
			45	24.0	2.5	+28
23.90	520	55				
			19	9.0	1.1	+27
27.25	406	55				
			38	13.9	2.1	-41
33.38	323	55				
			38	11.8	2.4	-41
39.04	302	75				
			54	13.8	5.0	+9
46.61	210	110				
			64	14.5	7.0	+8
54.97	242	110				
			53	9.9	4.9	+14
61.50	131	75				
			59	6.7	4.4	+19
68.51	96	75				
			62	6.0	4.2	+28
75.53	97	60				
			67	5.3	3.0	+72
82.85	60	30				
			74	3.9	2.2	+72
90.66	45	30				
			70	2.1	1.6	+56
97.83	14	15				
			160	3.3	1.4	+53
113.53	27	2				
			57	1.5	.1	+48
118.87	25	1				
			190	2.9	.2	+41
136.15	6	1				
			138	.6	.1	+92
148.18	2	0				
		Totals		153.3	44.4	+11.64

Again, using the multipliers for various wind angles off the bow, the bow-on and beam-on forces can be converted to resultant forces and moments for wind acting in any direction relative to these ships. These results are given for *SAMUEL GOMPERS* in Table 11 and for the *SPRUANCE* in Table 12.

As before, the current forces acting on the two military vessels are calculated by first deriving the bow-on and the beam-on force for a one-half knot current. These are as follows:

SAMUEL GOMPERS

F_{L_0} = 134# hull +115# propeller = 249#

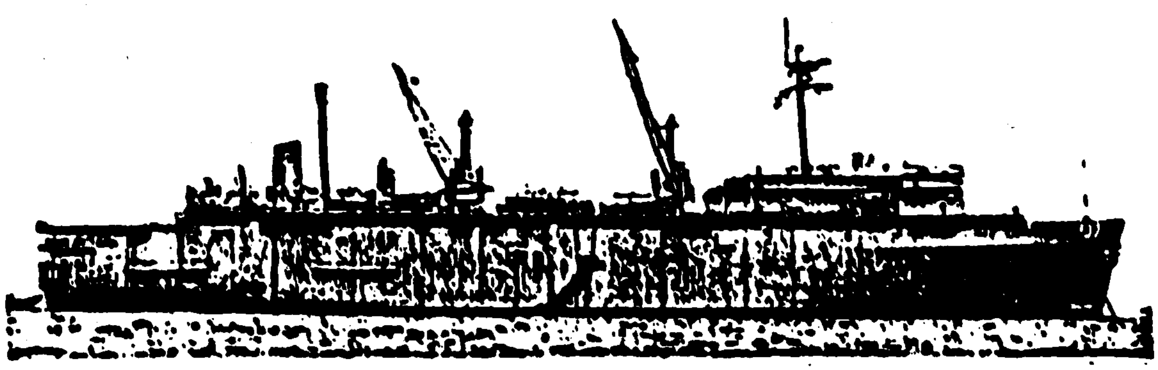
F_{T_0} = 9602#

SPRUANCE

F_{L_0} = 59# hull + 206# propeller = 264#

F_{T_0} = 4987#

The corresponding distributions of forces and moments as functions of current angle off the bow are given in Tables 13 and 14.

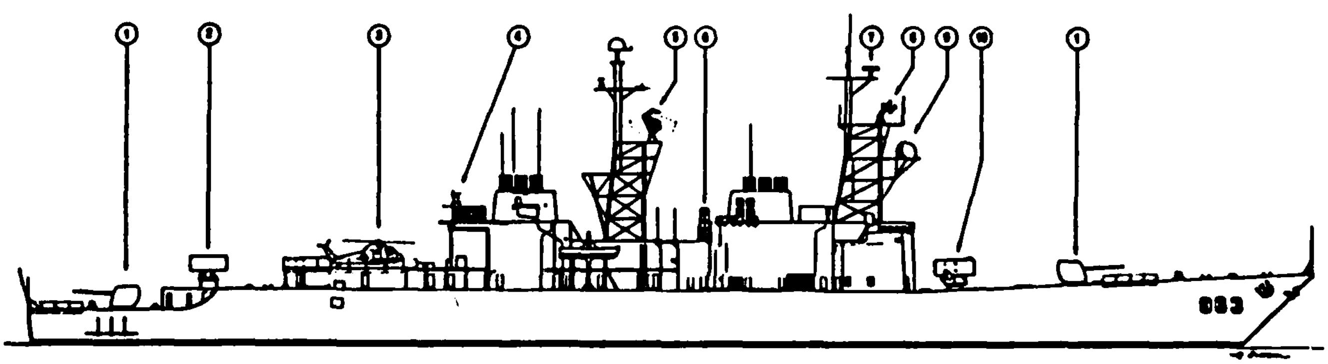


SAMUAL GOMPERS, AD 37

FIGURE 3

Table 11: Wind Forces and Moments for the *SAMUEL GOMPERS* for a 40 Knot Wind

Wind Angle $\alpha°$	F_L Kips	F_T Kips	F_R Kips	*LCR*, Ft Fwd ⊕	Moment Ft-Kips
0	87.6	0	82.6	----	----
10	95.2	60.3	112.7	155	9347
20	115.7	118.5	165.6	155	18368
30	131.4	173.2	217.4	155	26846
40	122.6	222.6	254.1	140	31164
50	98.6	265.3	283.0	129	34224
60	65.7	299.9	307.1	91	27291
70	32.9	325.6	327.2	70	22792
80	8.76	341.1	341.2	41	13985
90	0	346.3	346.3	11	3809
100	-8.76	241.1	341.2	-44	-15008
110	-32.9	325.6	327.2	-75	-24420
120	-65.7	299.9	307.1	-108	-32389
130	-98.6	265.3	283.0	-138	-36611
140	-122.6	222.6	254.1	-150	-33390
150	-131.4	173.2	217.4	-166	-28751
160	-115.7	118.5	165.6	-166	-19671
170	-95.2	60.3	112.7	-166	-10010
180	-87.6	0	87.6	----	----



SPRUANCE DD 963

FIGURE 4

Table 12: Wind Forces and Moments for the *SPRUANCE* for a 40 Knot Wind

Wind Angle $\alpha°$	F_L Kips	F_T Kips	F_R Kips	*LCR*, Ft Fwd ⊗	Moment Ft-Kips
0	44.4	0	44.4	---	---
10	48.3	26.7	55.2	147	3925
20	58.7	52.4	78.7	147	7703
30	66.6	76.7	101.6	147	11275
40	62.2	98.6	116.6	133	13114
50	50.0	117.4	127.6	124	14558
60	33.3	132.8	137.0	99	13147
70	16.7	144.1	146.1	72	10375
80	4.4	151.0	151.1	48	7248
90	0	153.3	153.3	12	1840
100	-4.4	151.0	151.1	-24	-3624
110	-16.7	141.1	145.1	-49	-7061
120	-33.3	132.8	137.0	-76	-10093
130	-50.0	117.4	127.6	-100	-11740
140	-62.2	98.6	116.6	-110	-10846
150	-66.6	76.7	101.6	-123	-9434
160	-58.7	52.4	78.7	-123	-6445
170	-48.3	26.7	55.2	-123	-3294
180	-44.4		44.4	---	---

Table 13: Current Forces and Moments versus Current Angle off the Bow for the *SAMUEL GOMPERS*

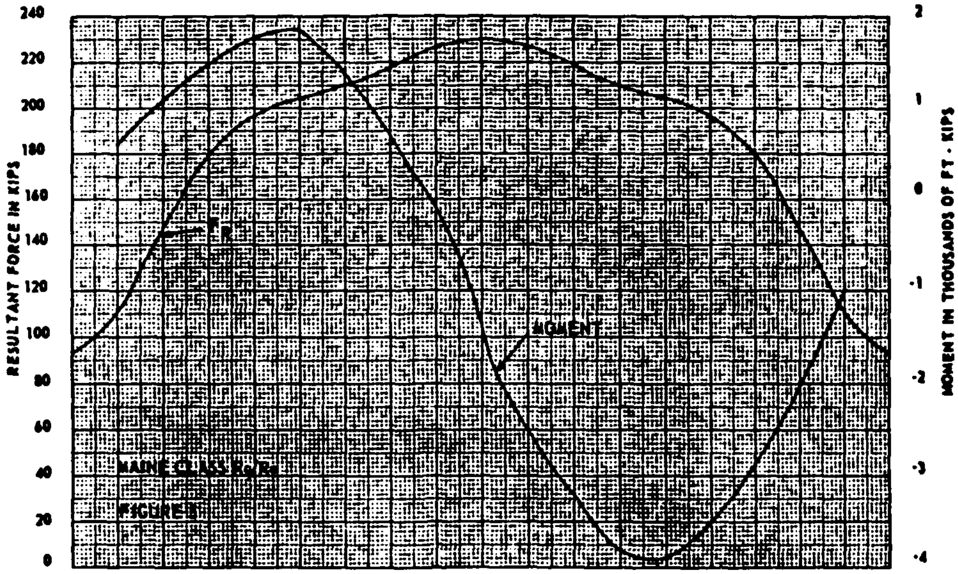
Current Angle α°	F_L Kips	F_T Kips	F_R Kips	*LCR*, Ft Fwd ⊄	Moment Ft-Kips
0	0.2	0	0.2	---	---
10	0.3	1.7	1.7	159	270
20	0.3	3.3	3.3	159	525
30	0.4	4.8	4.8	159	763
40	0.3	6.2	6.2	144	893
50	0.3	7.4	7.4	133	984
60	0.2	8.3	8.3	107	888
70	0.1	9.0	9.0	77	693
80	0	9.5	9.5	50	475
90	0	9.6	9.6	---	---

Table 14: Current Forces and Moments versus Current Angle off the Bow for the *SPRUANCE*

Current Angle α°	F_L Kips	F_T Kips	F_R Kips	*LCR*, Ft Fwd ⊄	Moment Ft-Kips
0	0.3	0	0.3	---	---
10	0.3	0.9	0.9	138	124
20	0.3	1.7	1.7	138	235
30	0.4	2.5	2.5	138	345
40	0.4	3.2	3.2	127	406
50	0.3	3.8	3.8	117	445
60	0.2	4.3	4.3	94	404
70	0.1	4.7	4.7	69	324
80	0	4.9	4.9	45	221
90	0	5.0	5.0	---	---

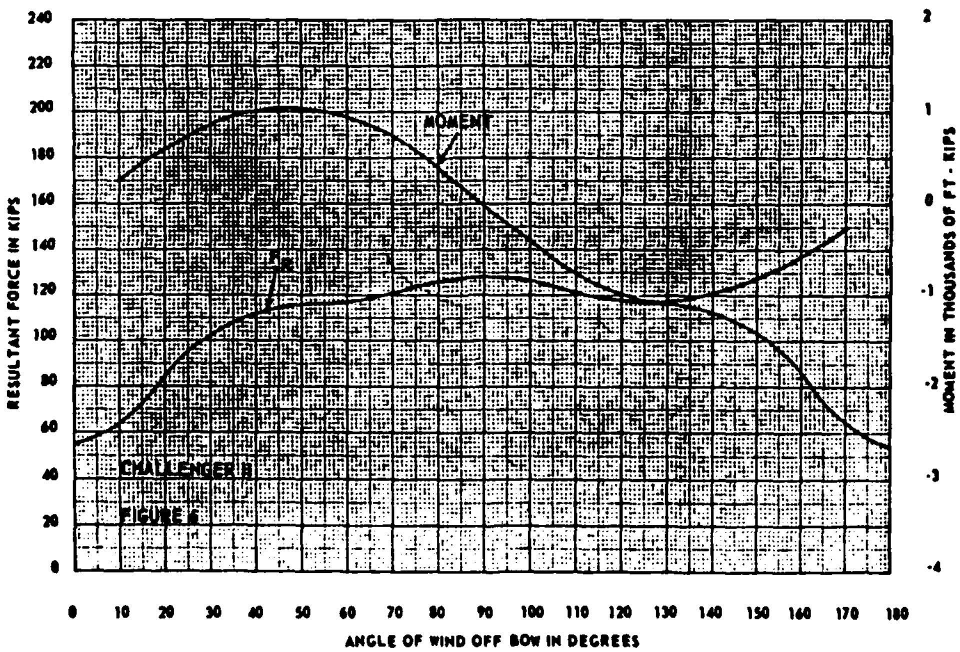
WIND AND CURRENT FORCE SUMMARIES

Plots of the force and moment of a 40 knot wind acting at various angles to each of these four vessels are given in Figures 5, 6, 7, and 8. Plots of the force and moment a one-half knot current acting at various angles to each of these vessels are given in Figures 9, 10, 11, and 12.



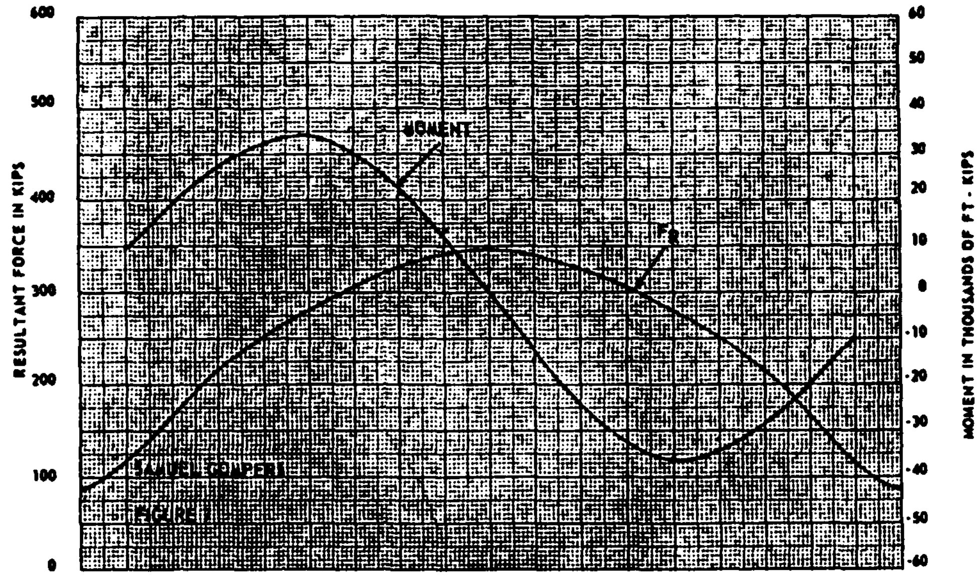
MAINE CLASS Ro/Ro

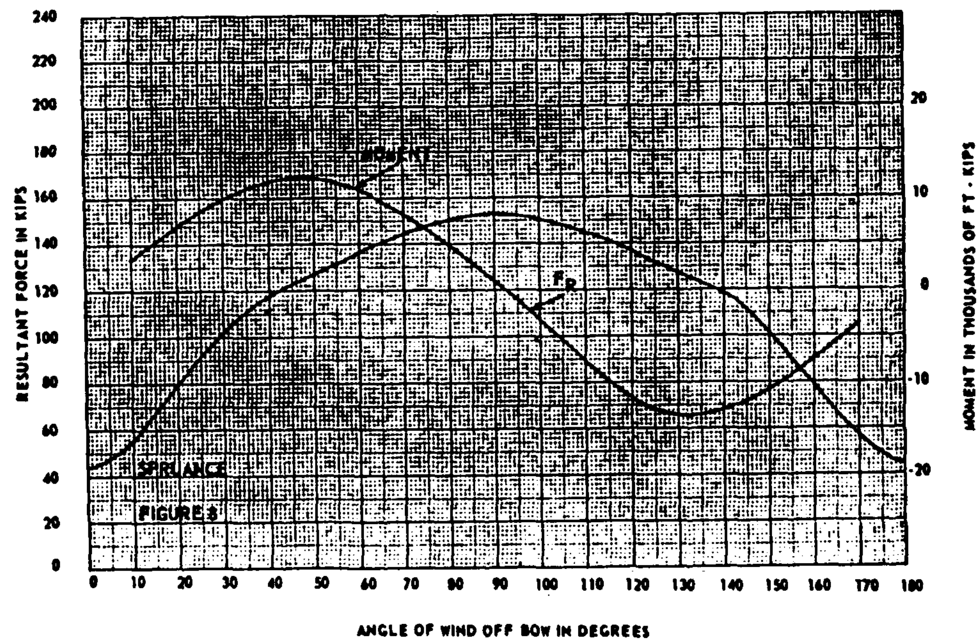
FIGURE 5

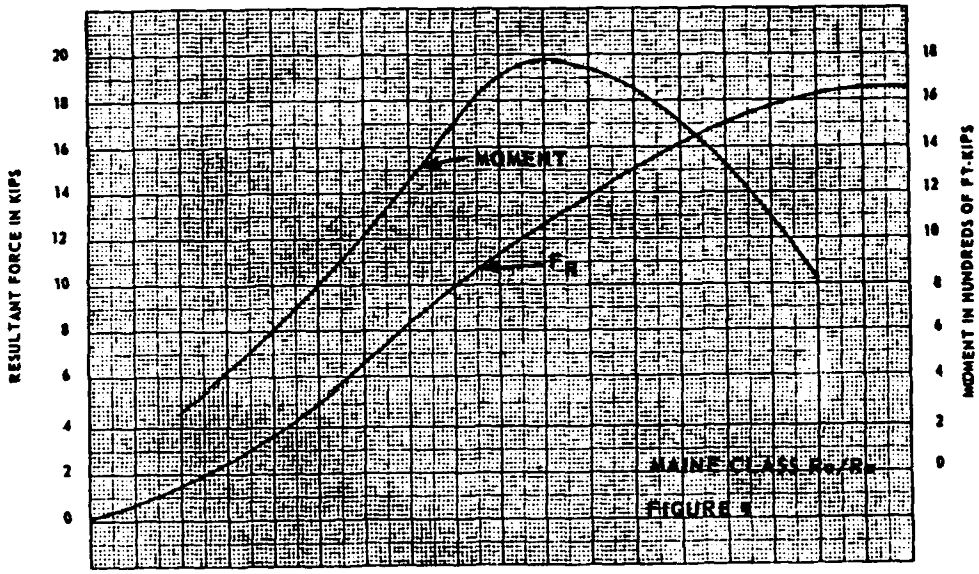


CHALLENGER II

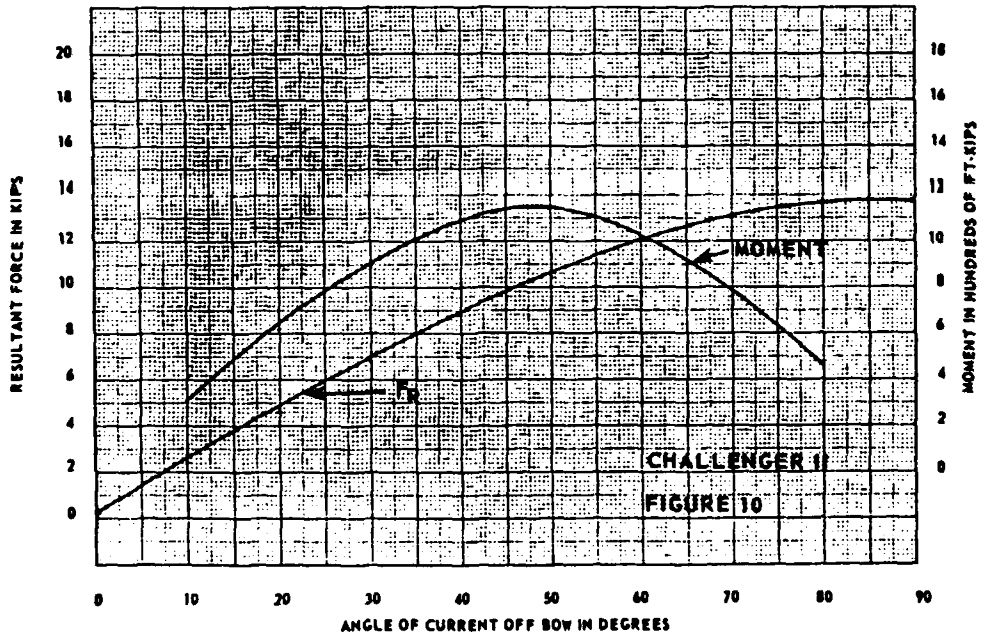
FIGURE 6


RESULTANT FORCE IN KIPS
600
500
400
300
200
100
0
MOMENT IN THOUSANDS OF FT - KIPS
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
MOMENT
FR
SAMUEL GOMPERS
FIGURE 7

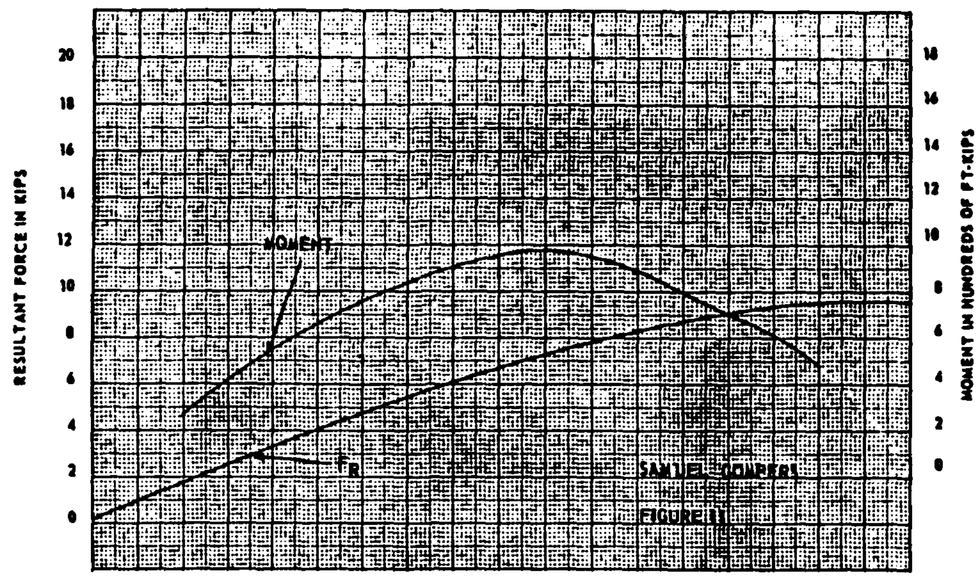

RESULTANT FORCE IN KIPS
240
220
200
180
160
140
120
100
80
60
40
20
0
MOMENT IN THOUSANDS OF FT - KIPS
20
10
0
-10
-20
MOMENT
FR
SPRUANCE
FIGURE 8
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
ANGLE OF WIND OFF BOW IN DEGREES

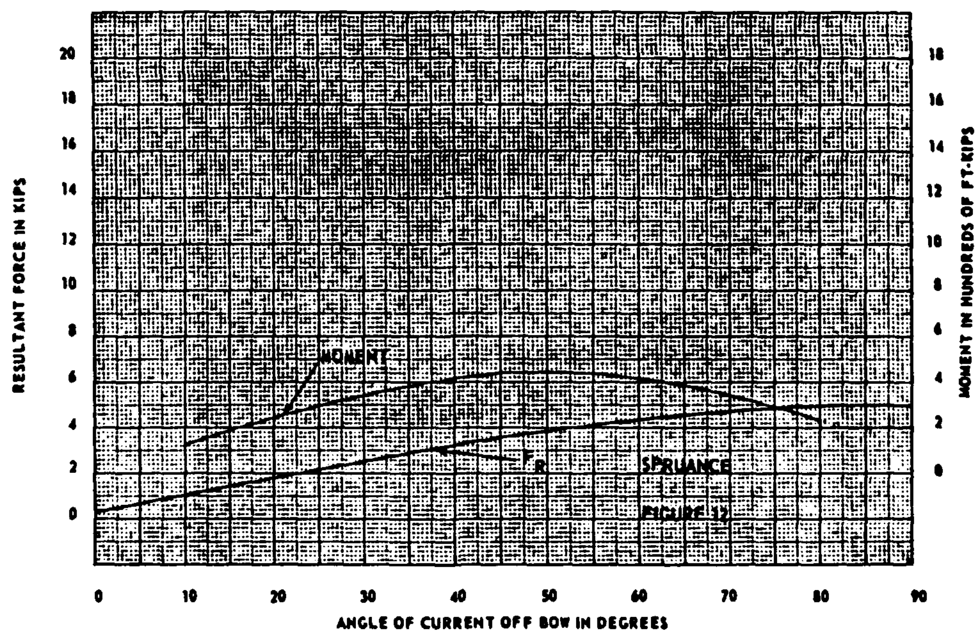


MAINE CLASS Ro/Ro
FIGURE 9



CHALLENGER I
FIGURE 10


RESULTANT FORCE IN KIPS
MOMENT IN HUNDREDS OF FT-KIPS
MOMENT
F_R
SAMUEL GOMPERS
FIGURE 11


RESULTANT FORCE IN KIPS
MOMENT IN HUNDREDS OF FT-KIPS
MOMENT
F_R
SPRUANCE
FIGURE 12
ANGLE OF CURRENT OFF BOW IN DEGREES

COMBINATION OF FORCES AND MOMENTS FOR MERCHANT VESSELS

The Maine Class Ro/Ro ships are to be moored from a single point moor about which the ship will be free to swing. Thus, the ship will tend to line up downstream of the moor at such a heading that the turning moments imposed by the wind and by the current are in balance. Assuming the maximum wind and current velocities, it can be seen from the tabulated and plotted data that the minimum resistance will be encountered in this condition, i.e., 93.8 kips of wind force plus 0.4 kips of current force for a total of 94.2 kips pull on the moor.

Actually the maximum pull on the moor will result from a beam-on current with the wind coming bow-on. In this condition the ship would be forced to swing to an angle of about 8° to the wind so that the wind moment would balance out the current moment. The resultant pull on the mooring under this condition would be 106.2 kips. It is not anticipated that there would be any significant wave force applied under these conditions.

The Challenger II Class ships are expected to be held by two point moors at bow and stern. With this type of mooring it could be anticipated that the greatest forces would be generated when both wind and current come from abeam. However, when it is considered that the maximum wind moment is generated with the wind at 50° off the bow, the greatest mooring loads occur with the wind at this angle and the current abeam.

Under the above condition the loading on the forward moor, athwarthships to the vessel is 75.9 kips and on the after moor, 35.6 kips. If the tie-up should be such that the after line from the ship to the mooring buoy applies no fore and aft load as the ship moves astern then an additional 76.3 kip load will be applied to the forward moor in the longitudinal direction. This will give a resultant of 107.6 kips applied to the forward moor. Since the wind is approaching a beam on condition in this situation an additional 5% should be added for wave induced loadings and each of the two moorings should have a minimum rating of 113 kips.

COMBINATION OF CURRENT FORCES AND MOMENTS FOR MILITARY VESSELS

Both the destroyer tenders and the submarine tenders are expected to be moored fore and aft and these moorings are to be capable of supporting the

tender plus one or more ships alongside for upkeep. The AD 37 Class destroyer tender and the DD 963 Class destroyer have previously been selected as representing the worst case condition insofar as wind and current effects are concerned.

Data on multiple moorings on different types of ships are non-existent. The closest approximation that can be made on such a mooring combination is to take data from multiple moorings of the same type of ship and use those as a guide for deriving characteristics of the nested ships to be moored at Diego Garcia. The basic equation used for this was taken from "Forces on Ships Moored in Protected Waters" by Ronald Altman, Hydronautics Report 7096-1, July 1971. This equation, and the accompanying tabular explanation, is reproduced in Figure 13.

It can be noted that the terms used vary with the number of ships in the nest and the coefficients vary with the type of ship. Here we have elected to use the lower set of coefficients and to apply those coefficients to the beam-on transverse force of the ship that they represent in the nest. Three cases will be derived. Case I is for the AD with a DD to windward and a DD to leeward. Case II has the AD with two DDs to leeward. Case III has the AD with three DDs to leeward. In all cases the beam-on transverse force will be that applied by a 40 knot wind plus a 1/2 knot current; in other words wind and current are coming from the same direction. The results of this calculation, including longitudinal force, transverse force, and resultant force for the three cases are tabulated in Table 15 and plotted in Figure 14.

Wind Lateral Forces in Multiple Mooring Configurations

Ship Model	Ship Type	Position in Mooring	First (Windward)	Second (Of Three or More Ships)	Third (Of Five or More Ships)	Leeward Ships (Third of Four, Fourth and Fifth of Six, Fourth, Fifth and Sixth of Seven, etc.)	Last (Most Leeward)
		Shape of Force vs Yaw Curve $0^\circ \le \phi \le 180^\circ$	$K_1 \cdot \sin \phi$	$K_2 \cdot \sin 3\phi$	$K_3 \cdot \sin 3\phi$	$K_4 \cdot (1-\cos 4\phi)$	$K_5 \cdot (1-\cos 4\phi)$
		Amplitude of Force vs Yaw Curve, Relative to Force on Single Ship Moored Alone	K_1	K_2	K_3	K_4	K_5
CVE-55 SS-212	Hull Dominant; Little Superstructure		1.00	0.20	No Data Suggest Using 0.16	0.35	0.44
EC-2 DD-692	Standard Profile, Considerable Superstructure		1.00	0.14	0.11	0.13	0.30

$$Y = Y_{90^\circ\text{-Single Ship}} \left(K_1 \sin \phi + K_2 \sin 3\phi + K_3 \sin 3\phi + K_4 (1-\cos 4\phi) + \ldots K_5 (1-\cos 4\phi)\right) \qquad (24)$$

where $Y_{90^\circ\text{-Single Ship}}$ is calculated from Equation (13) for the particular type of ship under consideration.

EQUATION EXTRACTED FROM HYDRONAUTICS, INC. REPORT

FIGURE 13

Table 15: Wind Plus Current Forces on Nested Tender and Destroyers

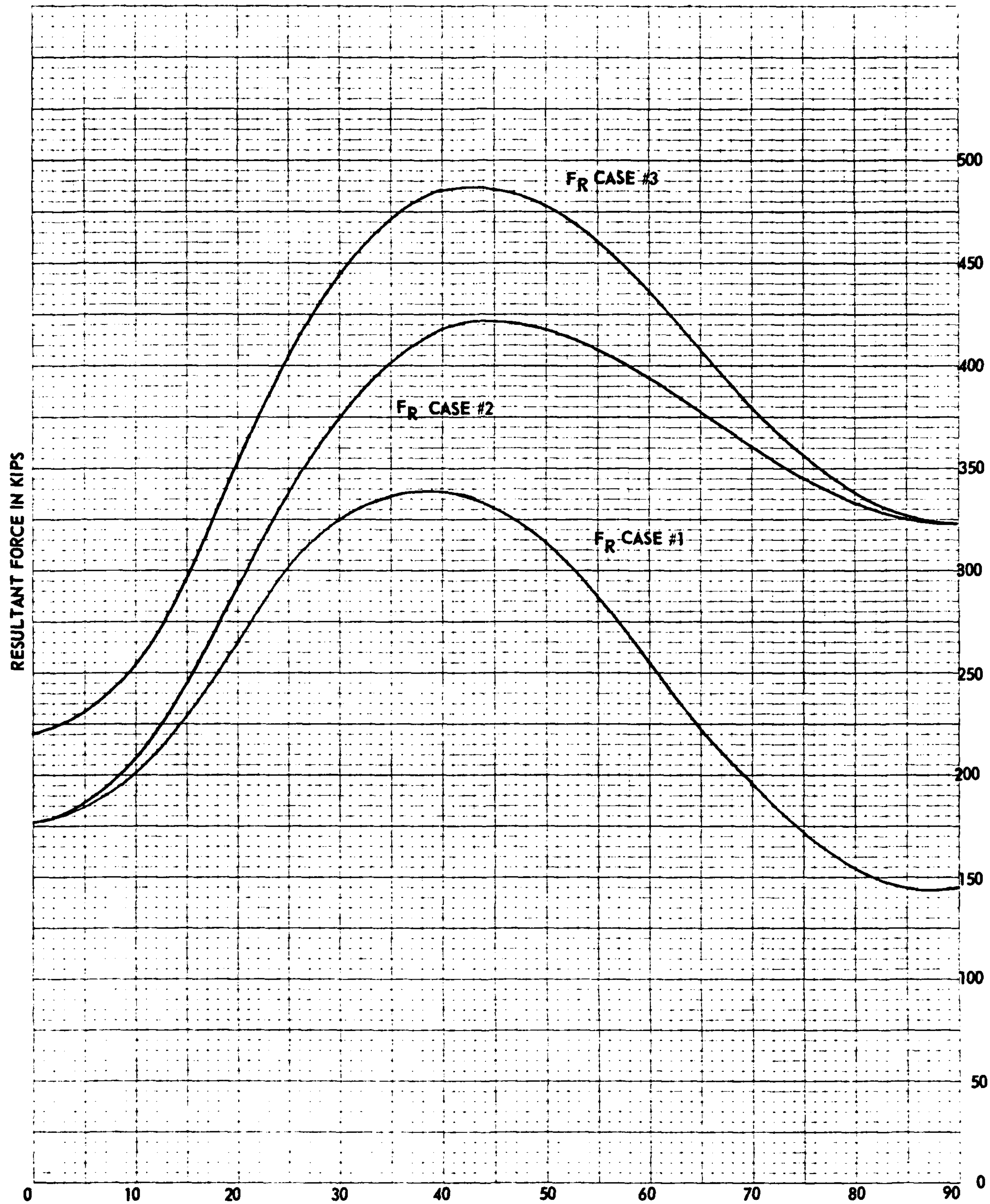
	Case I			Case II			Case III		
$\alpha°$	F_L	F_T	F_R	F_L	F_T	F_R	F_L	F_T	F_R
0	177.2	0	177.2	177.2	0	177.2	221.9	0	221.9
10	192.6	57.6	201.0	192.6	83.3	209.4	241.2	87.1	256.4
20	234.1	126.9	266.3	234.7	176.7	293.8	293.1	193.7	351.3
30	265.8	190.6	327.1	265.8	266.4	376.3	332.9	297.1	446.2
40	248.1	232.3	339.9	248.1	333.6	415.7	310.7	373.4	485.8
50	199.4	241.2	313.0	199.4	368.2	418.7	249.6	408.0	478.3
60	132.9	221.3	258.1	132.9	371.0	394.1	166.4	401.7	434.8
70	66.5	185.8	197.3	66.5	353.7	359.9	83.2	370.6	379.8
80	17.7	153.6	154.6	17.7	333.1	333.6	22.2	337.9	338.6
90	0	140.9	140.9	0	324.3	324.3	0	324.3	324.3

The maximum resultant forces applied to the forward mooring at an angle of about 45° to the hull centerline would be:

Case I: 340 kips
Case II: 419 kips
Case III; 486 kips

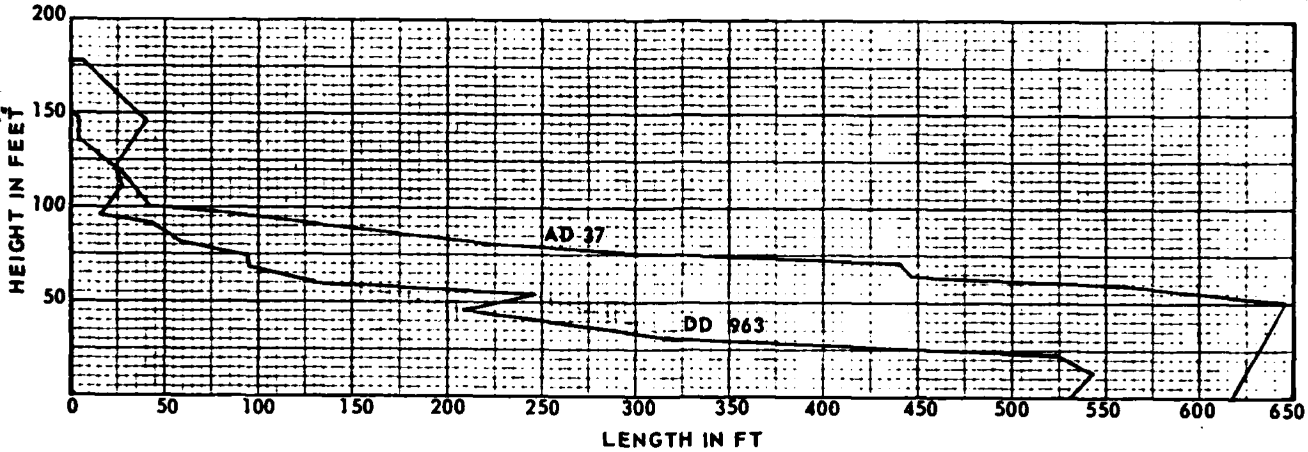
These mooring load curves in Figure 14 do not appear realistic leaving some doubt as to whether the Hydronautics suggested equation is applicable in the case where one of the ships is significantly larger than the others. As a result of this doubt, another technique has been adopted which seems to depict more realistically the forces that would act on the nested tender and destroyers for the three cases cited above.

First it is of interest to compare the profiles of the AD 37 and the DD 963. In Figure 15 the effective wind loading length for each of these ships is plotted against height. In a situation where a destroyer is alongside and upwind of the tender, the wind shadow cast by the destroyer in a transverse wind would be almost total up to a height of 45 feet above the waterline since the hull and deckhouses extend out to the maximum beam over the effective lengths shown. Similarly, if the tender or another destroyer were upwind of the DD 963, they would cast a slightly greater wind shadow on the downwind destroyer.



WIND PLUS CURRENT FORCES ON NESTED TENDER AND DESTROYERS

FIGURE 14



EFFECTIVE WIND LOADING LENGTH VERSUS HEIGHT FOR THE AD 37 AND DD 963

FIGURE 15

Above the 55 foot height, the destroyer superstructure steps in from the maximum beam to the extent that winds would not be influenced by the shadowing effect and would close back in to act upon the superstructure configuration. The basic result is to reduce the transverse 40 knot wind force on a shadowed destroyer from 153.3 kips to 42.2 kips. This force reduction is 111.1 kips.

For the three cases of nesting conditions the combined transverse 40 knot wind force would be as follows:

Case I:	Upwind DD:	153.3 kips
	AD: 346.3 - 93.1	253.2 kips
	Downwind DD: 153.3 - 111.1	42.2 kips
	Total 40 knot wind force	448.7 kips
Case II:	AD	346.3 kips
	1st Downwind DD: 153.3 - 111.1	42.2 kips
	2nd Downwind DD: 153.3 - 111.1	42.2 kips
	Total 40 Knot Wind Force	430.7 kips
Case III:	AD	346.3 kips
	1st Downwind DD: 153.3 - 111.1	42.2 kips
	2nd Downwind DD: 153.3 - 111.1	42.2 kips
	3rd Downwind DD: 153.3 - 111.1	42.2 kips
	Total 40 Knot Wind Force	472.9 kips

It is assumed that there will be no noticeable shadowing effect that will reduce the 0.5 knot current forces acting on the hulls. Also, it can be assumed that

the longitudinal forces due to both wind and current will be equal to the sum of those forces for the individual ships. Assuming wind and current acting from the same direction, the total transverse and longitudinal forces for the various cases will be:

	F_{L_O}, Kips	F_{T_O}, Kips
Case I	177.18	468.28
Case II	177.18	450.28
Case II	221.84	497.46

The same technique as used before is applied in developing the force versus angle curves for the nested ships. Also it is assumed that the destroyers are secured alongside the tender so that the center of lateral resistance for both wind and current is at the fore and aft center of the nested group. The results of these calculations are tabulated in Tables 16, 17, and 18 and are plotted in Figures 16, 17, and 18.

It may be noted that the maximum values of the resultant force curves occur when the wind and current are abeam. These values are:

Case I: 468.3 kips
Case II: 450.3 kips
Case III: 497.5 kips

The results are slightly higher than those obtained with the Hydronautics equation and are a maximum at 90° wind and current angle rather than at 45°. However, the curves do appear more realistic and are believed to be of greater accuracy.

Table 16: Wind Plus Current Forces on Nested Tender and Destroyers

Case I: One Destroyer on Each Side of Tender

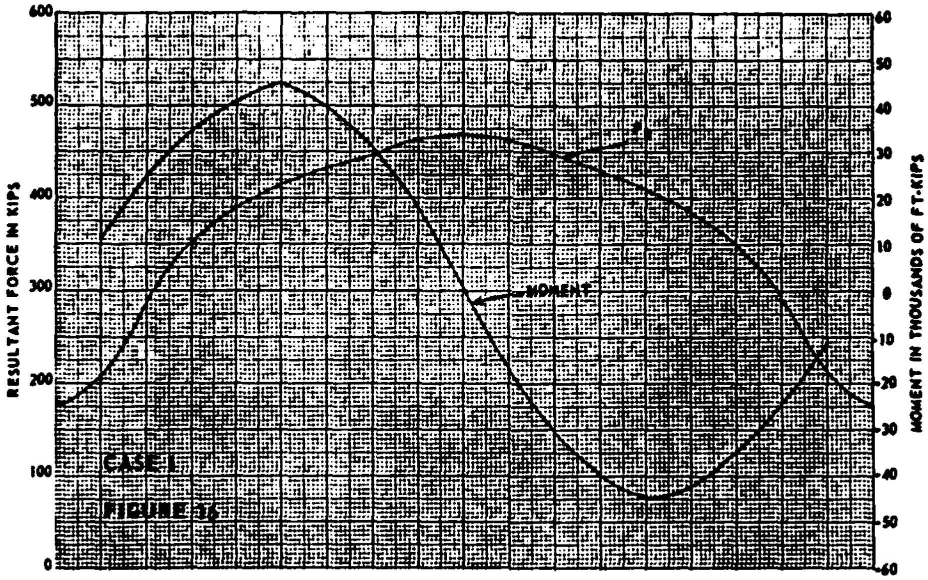
Wind Angle $\alpha°$	F_L Kips	F_T Kips	F_R Kips	Moment Ft-Kips
0	177.2	0	177.2	------
10	192.6	81.5	209.1	12386
20	234.1	160.2	283.6	24346
30	265.8	234.1	354.2	35577
40	248.1	301.1	390.1	41275
50	199.3	358.7	410.4	45246
60	132.9	405.5	426.7	40057
70	66.4	440.2	445.2	30105
80	17.7	461.3	461.6	18648
90	0	468.3	468.3	0
100	-17.7	461.3	461.6	-18648
110	-66.4	440.2	445.2	-30105
120	-132.9	405.5	426.7	-40057
130	-199.3	358.7	410.4	-45246
140	-248.1	301.1	390.1	-41275
150	-265.8	234.1	354.2	-35577
160	-234.1	160.2	283.6	-24346
170	-192.6	81.5	209.1	-12386
180	-177.2	0	177.2	------

Table 17: Wind Plus Current Forces on Nested Tender and Destroyers
Case II: Two Destroyers Downwind of Tender

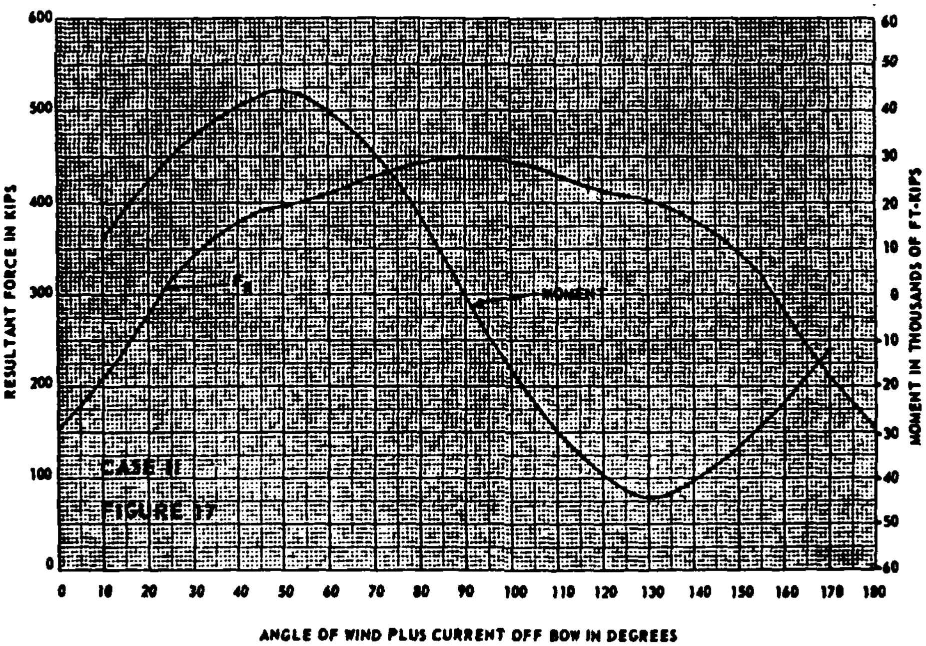
Wind Angle $\alpha°$	F_L Kips	F_T Kips	F_R Kips	Moment Ft-Kips
0	177.2	0	177.2	------
10	192.6	78.3	207.9	12259
20	234.1	154.0	280.2	24110
30	265.8	225.1	348.3	35242
40	248.1	289.5	381.3	40882
50	199.3	344.9	398.4	44818
60	132.9	389.9	412.0	39678
70	66.4	423.3	428.4	29822
80	17.7	443.5	443.9	18470
90	0	450.3	450.3	0
100	-17.7	443.5	443.9	-18470
110	-66.4	423.3	428.4	-29822
120	-132.9	389.9	412.0	-39678
130	-199.3	344.9	398.4	-44818
140	-248.1	289.5	381.3	-40882
150	-265.8	225.1	348.3	-35242
160	-234.1	154.0	280.2	-24110
170	-192.6	78.3	207.9	-12259
180	-177.2	0	177.2	------

Table 18: Wind Plus Current Forces on Nested Tender and Destroyers
Case III: Three Destroyers Downwind of Tender

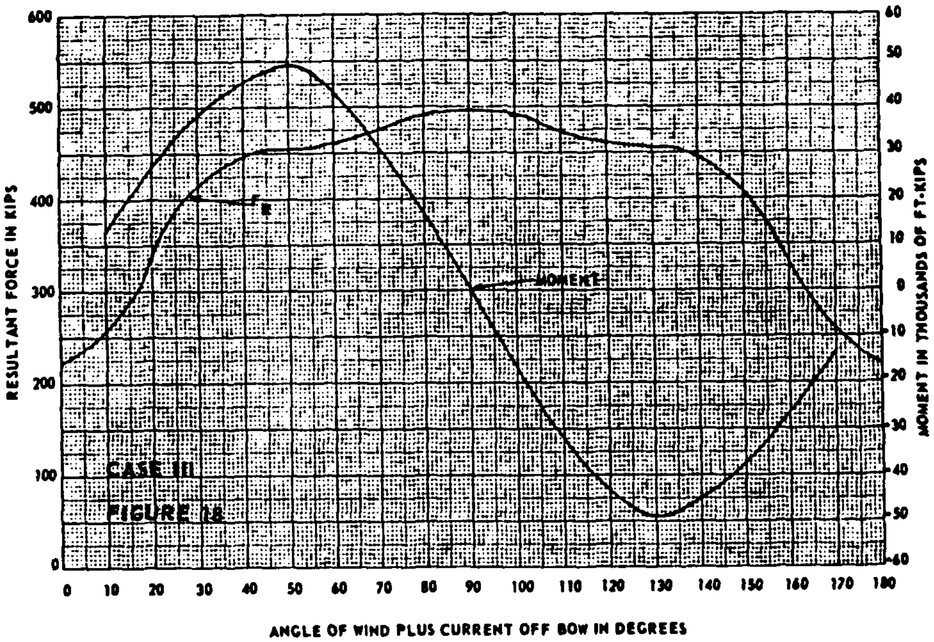
Wind Angle $\alpha°$	F_L Kips	F_T Kips	F_R Kips	Moment Ft-Kips
0	221.8	0	221.8	------
10	241.1	86.6	256.2	13428
20	293.1	170.1	338.9	26376
30	332.8	248.7	415.4	38563
40	310.6	319.9	445.8	44742
50	249.6	381.1	455.5	49048
60	166.4	430.8	461.8	43420
70	83.2	467.6	475.0	32628
80	22.2	490.0	490.5	20210
90	0	497.5	497.5	0
100	-22.2	490.0	490.5	-20210
110	-83.2	467.6	475.0	-32628
120	-166.4	430.8	461.8	-43420
130	-249.6	381.1	455.5	-44742
140	-310.6	319.9	445.8	-44742
150	-332.8	248.7	415.4	-38563
160	-293.1	170.1	338.9	-26376
170	-241.1	86.6	256.2	-13428
180	-221.8	0	221.8	------



CASE I
FIGURE 16



CASE II
FIGURE 17



600
500
400
300
200
100
0
RESULTANT FORCE IN KIPS
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
MOMENT IN THOUSANDS OF FT-KIPS
MOMENT
CASE III
FIGURE 18
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
ANGLE OF WIND PLUS CURRENT OFF BOW IN DEGREES

APPENDIX A

TECHNIQUE FOR CALCULATING WIND AND CURRENT FORCES ACTING ON SHIP HULLS

William H. Hunley
Norman W. Lemley

Ship Maneuvering, Navigation, and Motion Control

Section 1
Maneuvering Systems

1.1 Definitions. A surface ship *maneuver* can be broadly defined as an acceleration in a horizontal plane which may be either voluntary or involuntary. A voluntary acceleration results from a controlled force applied by a propeller, rudder, tug, or line while an involuntary acceleration normally stems from wind forces, current forces, or wave action. A ship has adequate maneuvering control when it can apply controlled forces of sufficient magnitude to overcome the involuntary forces encountered plus the additional force necessary to move the ship along a selected path at a desired rate of speed.

Mooring is a term applied to the operation of anchoring a vessel in a harbor, securing to a mooring buoy, or securing to a wharf or quay by means of chains or ropes. Mooring means to make a vessel fast to a buoy, quay or wharf, or by anchoring but, in addition the term is also used as a noun to describe the hardware involved in the securing. A moored vessel need not necessarily be truly stationary but may, in some types of moors, by free to swing around a single anchor on a chain or around a buoy to which the vessel is secured. Similarly, a moored ship may be free to rise and fall with the tide or to take on oscillatory motions in response to the action of waves on the hull. In this respect a moored vessel is restricted to a limited amount of movement and is restrained only to the extent necessary to keep that movement within well defined bounds.

1.2 Environmental Forces. The forces acting on a moored ship include those imposed by the environment and those opposing forces that are applied to keep the ship stationary or in a desired position and attitude. These forces are involved when mooring to piers and quays, mooring to buoys, anchoring, or when dynamically positioning a ship. The environmentally imposed forces result from wind, current, tidal action, and wave action.

Of primary concern in holding a ship stationary is opposing forces resulting from wind and current action. Tidal forces, aside from tidal currents, are essentially irresistible forces; the resulting vertical movement of the ship must be allowed for and cannot be opposed. Similarly, the wave forces acting on a stationary ship are essentially oscillatory in nature; they can be minimized by reorienting the ship or by detuning its natural response but little can be done to oppose the oscillatory ship motions resulting from wave action. However, a mooring or dynamic positioning system must be designed to adapt to wave imposed motions. Thus, the brief discussion herein of the environmental constraints involved in a mooring or a dynamic positioning system design will be limited to wind and current forces, not waves nor tides.

The literature is replete with dissertations on wind and current forces acting upon floating bodies. However, when a designer is faced with the task of calculating the forces and moments acting on a ship while moored or while dynamically positioned, he is hard pressed to sift out those which give the most reasonable answers. The method given below for wind force and moment calculation and that given for current force calculation are presented in simplified form for design use and appear to fit reasonably well the majority of the published data.

a. Wind Force Calculations. Air moving across a water surface has a varying velocity with altitude due to the interaction between the surface and the air mass. Saunders (1957)[1] evaluated several published velocity distributions and came to the conclusion that the most consistent average of various data was one where the velocity varied as the fifth root of the height above the surface. This can be expressed as:

$$\frac{V}{V_0} = \left(\frac{h}{h_0}\right)^{0.2} \tag{1}$$

where V is the airstream velocity at any height h and V_0 is a measured airstream velocity at some standard height h_0 above the surface, Fig. 1.

Saunders (1957) also concluded that the best average of wind drag force data was expressed by:

[1] Complete references are listed at end of chapter.

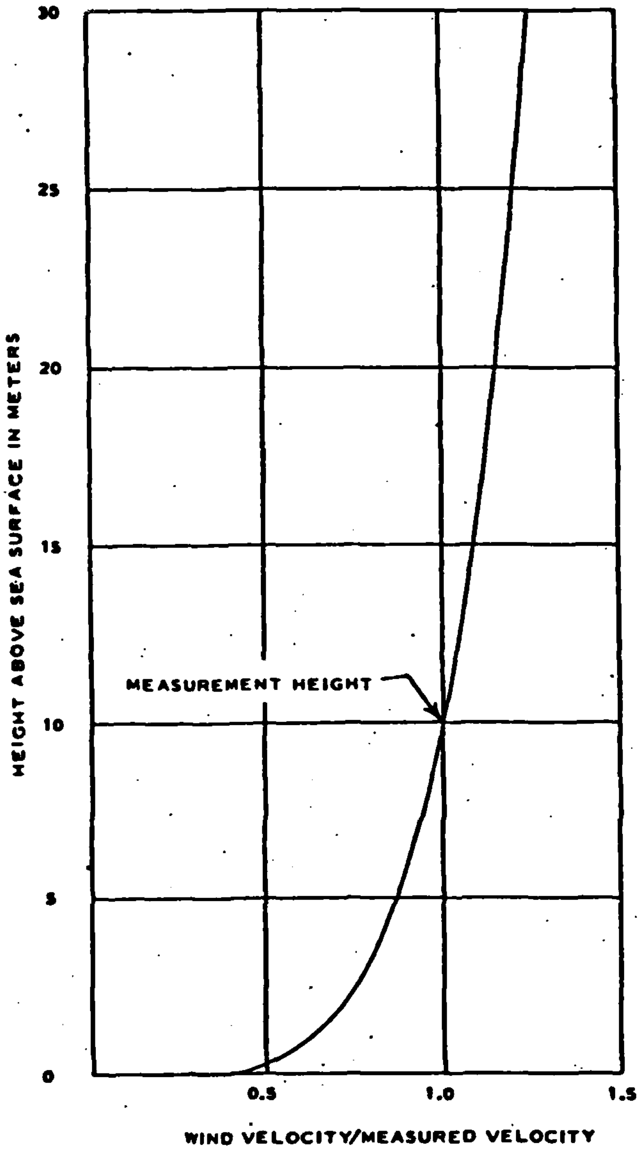


Fig. 1 Variation of wind velocity with height above water

$$F = 0.004 A V_w^2 \qquad (2)$$

where:

F is the drag force in lb
A is the projected area in ft^2
V_w is the airstream velocity in knots

When this equation is expressed in the terms:

$$F = C_D \frac{\rho}{2} A v^2 \qquad (3)$$

where:

ρ is the mass density of air
v is the wind velocity
A is the area with all terms in consistent dimensions,

then:

$C_D = 1.185$, a constant drag coefficient.

One standard used for wind velocity measurements over ground is a height h_0 of 10 m. However, since in many areas where calculations will be required the velocity may be measured at a different height, h_0 will be kept as a variable. To calculate the wind force on a projected strip of a ship of length l and height $h_2 - h_1$, the following expression is derived:

$$F = klV_0^2 \int_{h_1}^{h_2} \left(\frac{h}{h_0}\right)^{0.4} dh$$

$$F = \frac{klV_0^2}{1.4h_0^{0.4}} (h_2^{1.4} - h_1^{1.4}) \qquad (4)$$

When calculating wind forces and moments for any mooring or dynamic positioning application it is usually desirable to determine the force distribution with the wind at various angles to the ship and also the yawing moment that the wind can apply as a function of wind angle. The first step is to employ equation (4) to calculate the effective wind force that acts on the ship when the wind is bow on (angle of attack $\alpha = 0$ deg) and when the wind is abeam ($\alpha = 90$ deg). The abovewater areas to be included are all of those structures that the wind will impinge upon. Judgement can be used to estimate those elements that will always be in the lee of other elements and these can be neglected. However, *in calculating bow-on drag forces it should not* be assumed that lower parts of a midship deckhouse will be in the lee of a forecastle deckhouse, for example, since the wind will close in abaft the forecastle and apply its full force amidships. Similarly, smaller structures such as port and starboard kingposts should both be included and allowance should be added for rigging and antennas.

When making the profile force calculations, the longitudinal location of each element should be noted and the moment from the midship section determined. These moments can then be summed and divided by the transverse force factor to obtain the center of lateral resistance. A typical cargo ship wind force calculation for a one knot wind acting bow-on and beam-on is given in Table 1. Here it has been assumed that the wind velocity, V_0, was measured at a height of 10 meters above the surface. In this case the dimensions are in meters and the unit forces are expressed in Newtons. The typical ship used is that depicted in Fig. 10 of Chapter III.

Once the side force for a beam-on wind, the axial force for a bow-on wind, and the center of lateral resistance have been calculated, the force pattern for wind action at various angles of attack can be derived. Both model and full scale tests have demonstrated that this is not a simple sine-cosine relationship but is a complex pattern resembling the lift, drag, and center of pressure characteristics of an airfoil.

As the wind angle of attack off the bow, α, increases from zero, there develops both an increase in the axial force and an increase in the side force, with the latter analogous to the lift on an airfoil. The center of pressure of the side force remains at about the quarter length of the hull from the bow

Table 1—Forces for a One-Knot Wind on Beam and on Bow of Sample Ship

Above-water Region	h_2	h_1	l	b	LCP from ⊠	$\frac{F_T}{V_0^2}$ N	$\frac{F_L}{V_0^2}$ N
	Dimensions meters						
Forecastle to Fr 45	10.27	0.00	31.88	24.63	73.58	45.34	35.02
Bulwark Fr 45 to ⊠	5.73	0.00	58.28	24.63	29.14	36.6.	–
Kingpost 1 (× 2)	28.44	9.57	2.19	2.19	58.00	10.16	10.16
Kingpost 2 (× 2)	24.63	9.57	2.19	2.19	35.30	7.79	7.79
Winch house 2	9.57	5.73	8.47	9.02	35.30	5.59	5.95
Kingpost 3 (× 2)	24.08	8.75	2.19	2.19	14.23	7.79	7.79
Winch house 3	9.02	4.94	7.65	9.02	14.23	5.17	6.10
Bulwark ⊠ to stern	5.46	0.00	92.17	24.63	−46.09	54.05	—
Kingpost 4 (× 2)	26.79	5.27	2.19	2.19	− 2.19	10.72	10.72
Kingpost 5 (× 2)	26.79	5.27	2.19	2.19	−25.73	10.72	10.72
Bulwark to Upper Dk	6.55	5.46	27.89	24.63	−18.59	4.78	4.22
Upper Dk to Boat Dk	9.30	6.55	25.18	24.63	−17.50	12.05	11.79
Boat Dk to Bridge Dk	11.77	9.30	24.08	20.51	−17.22	11.63	9.91
Bridge Dk to Nav Bridge	14.23	11.77	19.96	20.51	−15.33	10.49	10.78
Nav Bridge to House Top	16.95	14.23	13.41	19.94	−12.04	8.33	6.80
Stack	21.88	14.23	6.28	4.39	−19.14	11.65	8.14
Kingpost 6 (× 2)	28.99	8.47	1.65	1.65	−46.51	8.21	8.21
Winch house 6	8.47	5.21	8.75	9.02	−48.13	4.69	4.84
Kingpost 7 (× 2)	24.08	8.75	2.19	2.19	−64.83	7.79	7.79
Winch house 7	8.47	5.21	7.65	9.02	−66.75	4.10	4.84
After Deckhouse	7.65	5.21	9.30	11.49	−84.80	3.64	4.50

(where: b = breadth of strip
LCP = longitudinal center of pressure)

Totals
F_{L_0}/V_0^2 176.07N
F_{T_0}/V_0^2 281.30N
Center of lateral resistance LCR 0.64 m fwd ⊠

while the side force, or lift force, increases almost linearly with increasing angle of attack. When the angle of attack reaches about 30 deg, a condition similar to a stall takes place. The lift force drops rapidly and the center of pressure moves back to the center of lateral resistance as the angle of attack increases from 30 to 90 deg. At an angle of attack of 90 deg, in other words a beam wind, the athwartship drag equals the calculated side force and acts at the center of lateral resistance. An inverse variation occurs as the angle of attack varies from 90 to 180 deg with the center of lateral resistance acting as the midpoint for the center of pressure movement.

Using the results of a calculation such as that shown for a sample ship in Table 1 to get the bow-on force, F_{L_0}, the beam force, F_{T_0}, and the center of lateral resistance, LCR from ⊠, the multipliers in Table 2 can be applied to derive the force distribution for any wind velocity at a series of angles of attack. The results of this calculation for a one-knot wind acting on the sample ship are given in Table 3. It can be noted that the angle of application of the resultant force differs from the angle of attack of the wind, Fig. 2.

The technique described above can be considered as reasonably valid for calculating wind drag on a generally ship-shaped form. For a much more detailed analyses and for an extensive list of references on this subject the reader is referred to a report by Altmann (1971).

b. Current Force Calculations. The movement of the body of water in which a ship is moored or dynamically positioned applies a downstream force to the hull that must be counteracted by the mooring or the dynamic positioning system to the extent that the ship does not move outside its established boundaries. When secured to a single-point mooring buoy, when swinging on a single anchor, or when being positioned dynamically, the boundaries are often established to allow the ship to move around to a heading where the current has a minimum effect, and thus the mooring or positioning system can be designed for this ad-

Table 2—Flow Force and Centers Multipliers

Flow Angle, deg α	$\frac{F_L}{F_{L_0}}$	$\frac{F_T}{F_{T_0}}$	$\frac{LCP \text{ from ⊠}}{\frac{L}{2} - LCR \text{ from ⊠}}$
0	1.000	0	—
10	1.087	0.174	0.500
20	1.321	0.342	0.500
30	1.500	0.500	0.500
40	1.400	0.643	0.451
50	1.125	0.766	0.415
60	0.750	0.866	0.325
70	0.375	0.940	0.225
80	0.100	0.985	0.133
90	0	1.000	0
100	−0.100	0.985	−0.133
110	−0.375	0.940	−0.225
120	−0.750	0.866	−0.325
130	−1.125	0.766	−0.415
140	−1.400	0.643	−0.451
150	−1.500	0.050	−0.500
160	−1.321	0.342	−0.500
170	−1.087	0.174	−0.500
180	−1.000	0	—

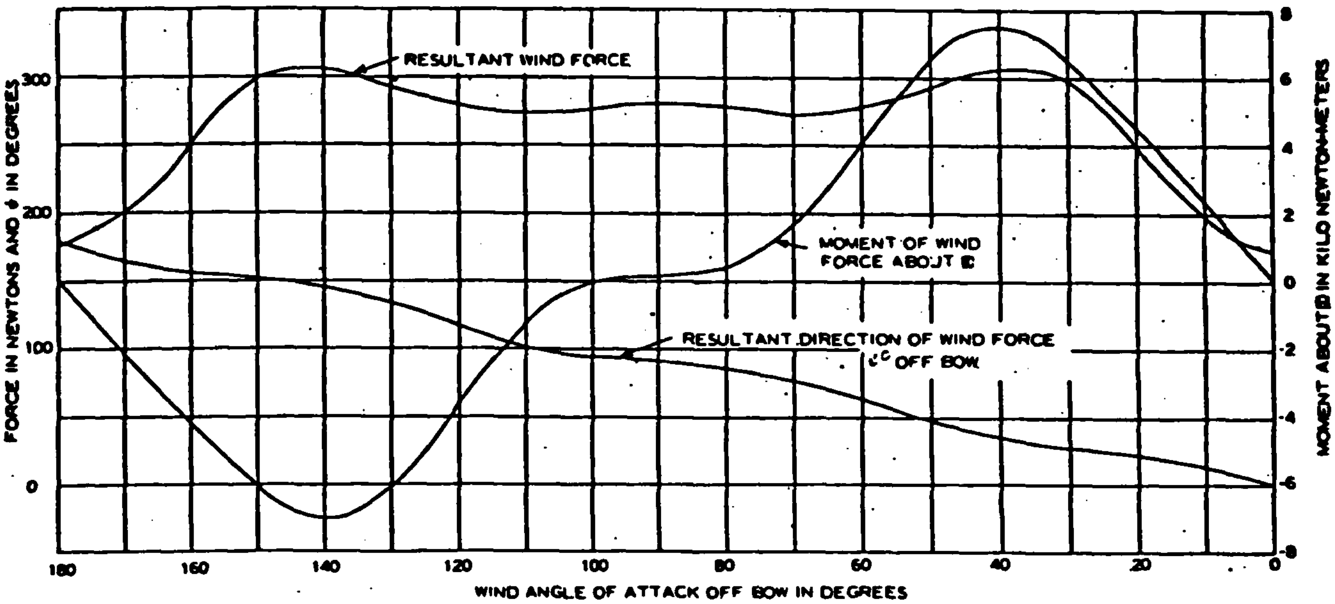


Fig. 2 Distribution of wind force factors for a one-knot-wind

aptation to minimal environmental forces. However, when moored to a pier, quay, or lock wall there probably will be no means of minimizing the current effect and the mooring hardware will be required to withstand the full brunt of the current force upon the hull.

As in the calculation of wind effects on the abovewater structure, the current forces must be calculated for any direction of flow relative to the hull and similarly the center of application of these forces must be determined. Again, there is a wealth of literature published on the subject (Altmann, 1971) but it is difficult to extract a simple means of calculating the effects of slow moving currents on a hull over a range of angles of attack.

A significant factor in the longitudinal force exerted on a stationary ship by a current is the drag of locked propellers which often can exceed the drag of the hull itself. Additionally, current speeds are frequently so low that the Reynolds Number, based either upon length or beam of the ship, is in a range where transitional flow occurs with a correspondingly wide variation in the drag coefficients. Thus, a simple answer to the calculation of current forces is difficult to come by but there is no guarantee that a much more complex calculation method will be any more reliable. Therefore, the calculation procedure outlined below, while admittedly simplified to the extreme, is probably as good as can be obtained within the current state of the art.

First, it will be assumed that the maximum section area of the underwater body of the hull, A_X, can be obtained and that the profile area, A_Y, is equal to the product of the mean underbody length and the draft. The resistance of a ship form to a bow-on current is extremely low. An average of some 60 ships from the SNAME Resistance Data sheets gives an average drag coefficient of 0.088 with a standard deviation of 0.039. Although there are numerous refinements that can be applied, it is doubtful whether they significantly improve the accuracy of simply using this average value. Similarly, if the spread of data for the beam-on resistance is examined it will be found that an athwarthships drag coefficient of 0.50 is a consistent average for determining the transverse resistance of a ship hull to a current.

Thus, for a ship type hull, without locked propellers, the axial resistance to a bow-on current can be calculated as:

$$F_{L_0} = \frac{\rho}{2} \times (0.088) \times C_X \times B \times T \times v^2 \qquad (5)$$

with all terms in consistent units;

Table 3—Wind Forces and Moments for the Sample Ship in a One-Knot Wind

Wind Angle, deg α	Resultant Force N	Resultant Angle, deg Ψ	Moment about ℄ $N-m$
0	176	0	0
10	197	14.3	2350
20	251	22.5	4431
30	299	28.0	6477
40	305	36.3	7516
50	292	47.4	6494
60	277	61.6	4067
70	272	76.0	1669
80	277	86.4	395
90	281	90.0	180
100	277	93.6	−36
110	272	104.0	−1298
120	277	118.4	−3668
130	292	132.6	−6075
140	305	143.7	−7118
150	299	152.0	−6153
160	251	157.5	−4209
170	197	165.7	−2137
180	176	180.0	0

the transverse resistance to a beam-on current can be calculated as:

$$F_{T_\theta} = \frac{\rho}{2} \times (0.50) \times L \times T \times \nu^2 \qquad (6)$$

where:

ρ = mass density of water
C_X = maximum section coefficient
L = mean underbody length
T = mean draft
ν = current velocity

The high axial resistance of locked propellers has been mentioned previously and this must be added to the axial resistance of the ship for other than dynamic positioning situations. A reasonable value is:

$$F_{L_\theta}/\text{Prop} = \frac{\rho}{2}(0.50)d^2\nu^2 \qquad (7)$$

where:

d = propeller diameter in consistent units

If the underwater profile of the ship is such that the center of its area is at a point other than midship section, the position of this lateral center of resistance, *LCR*, should be calculated.

According to the majority of available data the axial, or longitudinal resistance variation with the angle of attack of the current is strictly a function of the product of the bow-on current resistance, F_{L_θ} and the cosine of the attack angle. The athwartships resistance, on the other hand, is proportional to the 1.5 power of the sine of the attack angle, multiplied by the beam-on current resistance, F_{T_θ}.

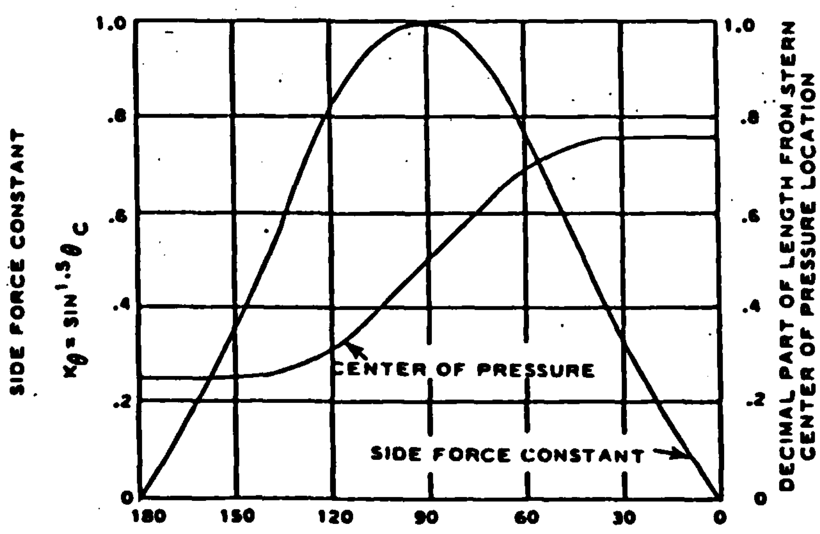
As with the wind resistance, the center of pressure is at the quarter-point from 0 to about 30 deg angle of attack of the current off the centerline. The center of pressure then moves rapidly back to the center of lateral resistance as the angle of attack reaches 90 deg. A similar movement of the center of pressure is associated with current angles off the stern. Thus, the center of pressure variation with angle of attack given for wind forces in Table 2 is also applicable to the centers of underwater current forces. These force and centers relationships are shown in Fig. 3.

The sample ship for wind force and moment calculations has a maximum underwater section area at load draft of 256 m² (2,755 ft²). The underwater profile area is 1,862 m² (20,038 ft²) with the center of lateral resistance located 1.4 m (4.7 ft) or 0.8 percent of the length forward of amidships. The propeller has a diameter of 6.7 m (22.0 ft). This gives a bow-on current force, F_{L_θ} of 6,109 N (1,375 lb) per knot squared and a beam-on current force, F_{T_θ} of 126,350 N (28,405 lb) per knot squared. Using the force and moment arm distributions of Fig. 3, the resultant forces and moments of Fig. 4 are obtained.

Ships are often moored in relatively shallow water and when a beam current acts on the hull its velocity is altered as it flows from one side of the ship to the other. The restricted passage between the hull and the floor of the body of water causes increased flow velocities under the ship bottom and around the bow and stern resulting in a greater athwartships force being applied to the ship. This increase in force is usually expressed as a drag coefficient plotted against the ratio of water depth, D, to ship draft, T. This drag coefficient augmentation in shallow water is shown in Fig. 5 as obtained from a large number of model tests; it should be applied instead of C_D = 0.50 whenever the D/T value is less than 8 to all current force and moment calculations.

c. Combination of Environmental Forces and Moments. For any mooring or dynamic positioning calculation it is expedient to establish a set of environmental conditions in which the system is expected to exert the controlling forces

Fig. 3 Current force and center relationships



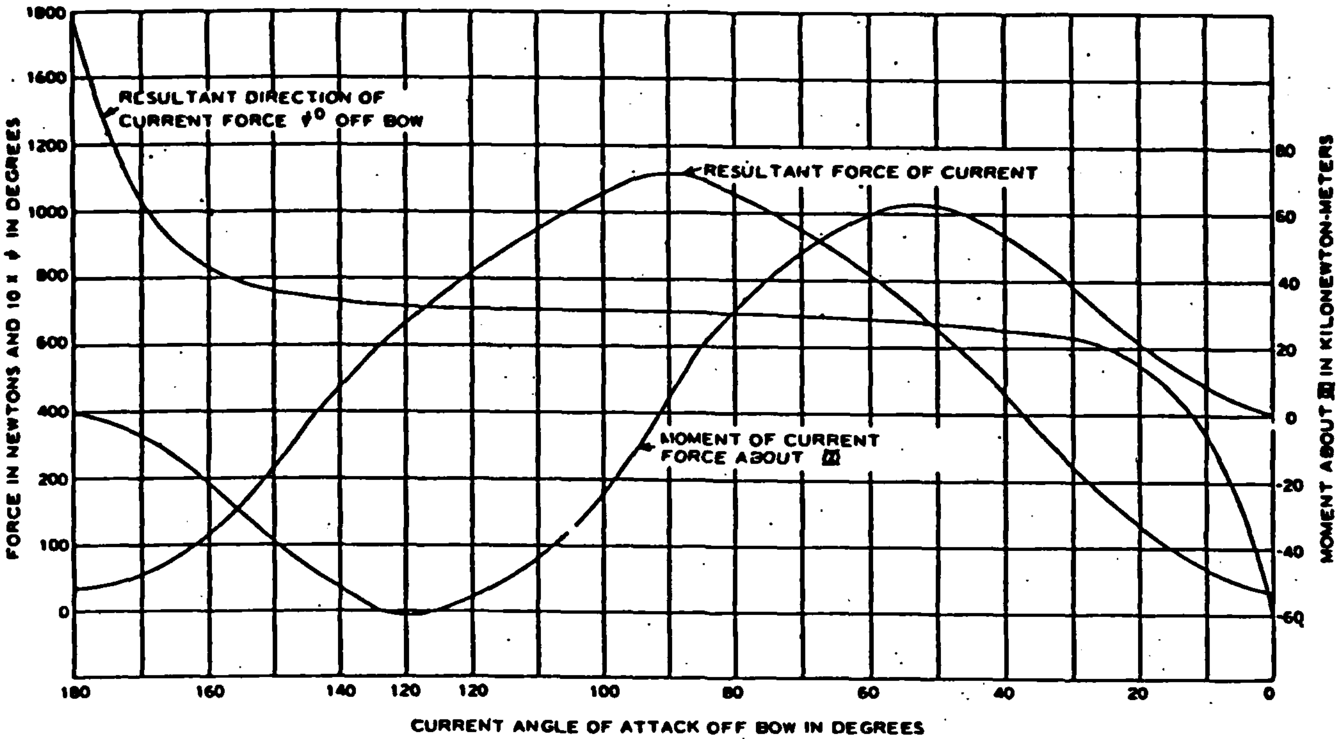


Fig. 4 Distribution of current force factors for a one-tenth knot current

and moments required to oppose the environmental forces and moments. These environmental specifications will generally be formulated as a wind velocity measured at a specified height, a current velocity in a specified depth of water, and, in some cases, a limiting range of directions over which the wind and current may be applied. It then becomes necessary to determine what will be the most critical combination of these forces and moments insofar as the mooring or positioning system design is concerned.

For each combination that appears critical, the forces and moments can be calculated. These will be resolved into longitudinal and transverse forces and moments about amidships and the wind forces, current forces, and moments can then be summed to give a single force, moment, and force direction.

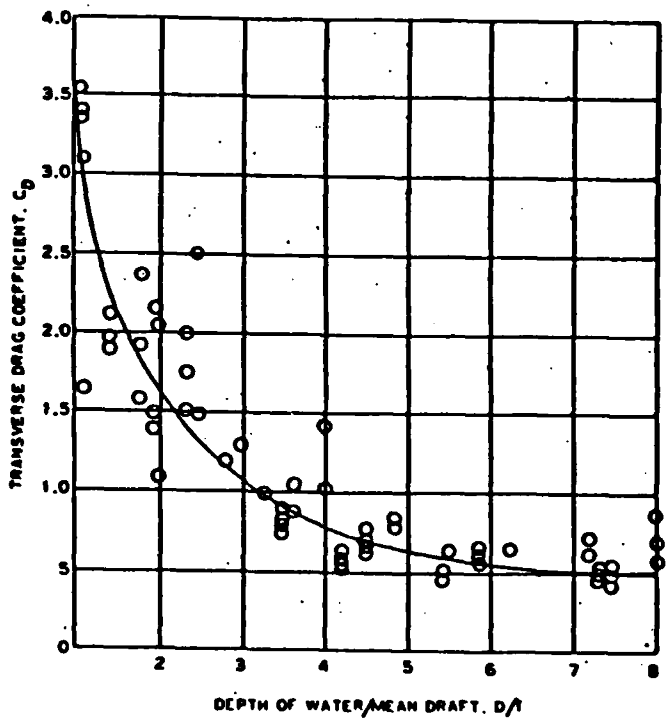


Fig. 5 Variation of drag coefficient in various water depths

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